NASA CR-137656

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REDUNDANT ACTUATOR DEVELOPMENT PROGRAM

(NASA-CR-137656) REDUNDANT ACTUATOR DEVELOPMENT PROGRAM Final Report (Boeing Commercial Airplane Co., Seattle) 170 p HC $6.25 CSCL 01C

N75-21289

Unclas G3/08 19962

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Final Report

April 1975

Prepared under contract NAS2-7966 Mod. No. 3 by

Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, Washington 98124

for
Ames Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-137656		
4. Title and Subtitle REDUNDANT ACTUATOR DEVELOPMENT PROGRAM		5. Report Date March 1975
		6. Performing Organization Code
7. Author(s) C. C. Chenoweth, D. M. Fain, C. I. Svensson		8. Performing Organization Report No. D6-46457
		10. Work Unit No.
9. Performing Organization Name and Address Boeing Commercial Airplane Company P.O. Box 3707 Seattle, Washington 98124		11. Contract or Grant No. NAS2-7966 Mod. No. 3
		13. Type of Report and Period Covered Contractor Final Report Ten Months
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

This study was monitored by Mr. V. B. Holland and Mr. W. R. Wehrend of Ames Research Center.

16. Abstract

Two concepts of redundant secondary actuator mechanization, applicable to future advanced flight control systems, have been studied to quantitatively assess their design applicability to an AST. The two actuator concepts, a four-channel, force summed system and a three-channel, active/standby system have been developed and evaluated through analysis, analog computer simulation, and piloted motion simulation. The quantitative comparison of the two concepts indicates that the force summed concept better meets performance requirements, although the active/standby is superior in other respects. Both concepts are viable candidates for advanced control application dependent on the specific performance requirements.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Redundant actuator Secondary actuator Flight controls Flight critical Active controls	Unclassified—Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	160	

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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FIGURES (Concluded)

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SYMBOLS AND ABBREVIATIONS

A	Area
A	Actuator channel A
A_c	Actuator channel A command
A_m	Actuator monitor channel A command (active/standby)
ampl	Amplitude
AST	Advanced supersonic transport
B	Backlash
B	Actuator channel B
B_c	Actuator channel B command
B_m	Actuator monitor channel B (active/standby)
C	Actuator channel C
C_c	Actuator channel C command
c.g.	Center of gravity
C_m	Actuator monitor channel C (active/standby)
c_p	Leakage coefficient
Hz	Cycles per second
C_1	Actuator cylinder no. 1
C_2	Actuator cylinder no.2
D	Damping
D	Actuator channel D (force summed)
dB	Decibels
DC	Direct current
D_c	Actuator channel D command

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D_{dm}	Modulator gain
deg	Degree
D_l	Load damping
D_p	Piston damping
e_c	Control valve voltage
$e_{c_{max}}$	Rated control valve voltage
$e_{c_{peak}}$	Observed maximum control valve voltage
ECSS	Electrical command and stability system
EC servo	Electrical command servo
F	Force
F	Farad
FAA	Federal Aviation Administration
F_f,F	Piston friction
F_o	Output force
f.s.	Full scale
FSAA	Flight simulator for advanced aircraft
H/Q	Handling qualities
HSAS	Hardened stability augmentation system
Hz	Hertz, cycles per second
IAS	Indicated air speed
IC	Initial condition
i_c	Actuator control valve current
i_m	Monitor control valve current
in.	Inches

in^3/s	Cubic inches per second
IVSI	Instantaneous vertical speed indicator
j	Imaginary number notation
K	Dynamic spring
k	Kilo
K_a	Servo amplifier gain
K_F	Amplifier gain
K_f	Position feedback gain
K_p	Valve pressure gain
K_{p1}	Valve pressure gain first stage
K_{p2}	Valve pressure gain second stage
K_s	Actuator rod stiffness
K_{s1}	Actuator backup structural stiffness
K_{s2}	Actuator rod stiffness
K_t	Mechanical reversion switch
K_v	Valve flow gain
K_{v1}	Valve flow gain first stage
K_{v2}	Valve flow gain second stage
K_x	LVDT gain
L	Actuator piston stoke
lbf	Pound force
Lm	Amplitude ratio
LVDT	Linear variable differential transformer
M	Mach number

m	Meter
mA	Milliampere
M_l	Load mass
M_p	Piston mass
MTBF	Mean Time Between Failure
N	Newton
n	Number of channels
P	Hydraulic pressure
Pa	Pascal
PR	Pilot Rating
Pr	Return pressure
Ps	Supply pressure
psi	Pounds per square inch
Q_{ECSS}	Body axis pitch rate–signal to ECSS
Q_{HSAS}	Body axis pitch rate–signal to HSAS
Q_L	Flow limit
R	Return
rad	Radians
s	Laplace variable
s, sec	Seconds
SAS	Stability augmentation system
SST	Supersonic transport
t	Flight time (used in reliability calculations)
V	Volts

X	Variable
X, X_o	Output position
$\dot{X}_o$	Output rate
X-ducer	Transducer
$X_{max}, X_{o_{max}}$	Maximum output position
$X_{peak}, X_{o_{peak}}$	Peak output position
β	Fluid bulk modulus
δ_{col}	Control column deflection
δ_{ecs}	EC servo output
δ_h	Horizontal stabilizer output deflection
δ_{hc}	Horizontal stabilizer position command
δ_{HSAS}	HSAS control law commands
δ_m	Output from mechanical control path
δ_{ms}	Master servo output
δ_{SAS}	SAS command
δ_{tm}	Trim motor output
θ	Angular displacement
$\dot{\theta}$	Angular rate
λ_A	Failure rate, actuator (failures/hour)
$\lambda_{A/S}$	Failure rate, active standby (failures/hour)
λ_c	Failure rate, channel (failures/hour)
λ_{hyd}	Failure rate, hydraulics (failures/hour)
λ_m	Failure rate, monitor (failures/hour)
λ_{servo}	Failure rate servo (failures/hour)

μ	Micro
σ	Real variable on the s-plane
τ	Time constant
ϕ	Phase angle
ω	Frequency
ω_B	Break frequency

NOMENCLATURE

ACTIVE/STANDBY:	Redundant actuator configuration that utilizes one actuator channel at a time. The active actuator controls the output, until deactivated, and then a standby actuator is activated to drive the output (para. 2.2.2.2.).
BLOCKING VALVE:	Two-position valve (open or closed) which functions to pass or block hydraulic fluid flow (para. 2.4).
BYPASS VALVE:	See blocking valve.
CASCADE FAILURE:	A domino failure effect, e.g., failure of a correctly-operating actuator channel caused by the failure of another actuator channel.
CENTERING DETENT:	A preloaded spring force which forces the system output to a specific position (para. 2.2.2.4).
COMPLIANCE:	Deflected motion of an element as a function of force, i.e., the inverse of stiffness (para. 2.2.2.3).
COOPER-HARPER: (PILOT RATING)	A method for rating aircraft flying qualities. A rating of 1.0 is highly desirable and 10.0 indicates major deficiencies (fig. 37).
CROSS-CHANNEL MONITORING:	A failure monitoring scheme that compares each actuator channel against another actuator channel.
DUAL FAIL-OPERATIVE:	Capable of operating after sustaining two malfunctions (para. 2.4.1).
DEADBAND:	Lack of response to low level command signals (fig. 11).
EQUALIZATION:	A method to reduce force fight in a force summed system (para. 2.2.2.3).
FAIL-OPERATIONAL:	Capable of operating after sustaining a malfunction (para. 2.4.1).
FLIGHT CRITICAL:	Essential for continued safe flight.
FORCE SUMMING:	A parallel active mechanization where two or more actuators are connected to a common output and operate simultaneously. (para. 2.2.2.2).

HANDLING QUALITIES:	Qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role (fig. 37).
HARDOVER:	100% signal or position output. A hardover failure indicates that an actuator has been driven to its stops.
HIGH GAIN FAILURE:	System response to an input command at a higher than designed (normal) gain. Usually caused by an open feedback loop (para. 3.4.1.4).
HYSTERESIS:	The difference in the input command signal required to produce the same output position during a single cycle of input throughout a specified range when cycled at a rate below that at which dynamic effects are significant (fig. 11).
IN-LINE MONITORING:	A failure monitoring scheme to detect failures within a redundant actuator channel without voting what the other channels are doing.
LOAD SHARING:	The working together of force summed actuators (para. 2.2.2.3).
MINIMUM-SAFE OPERATION:	Pilot rating greater than 6.5, based on Cooper-Harper scale, indicating aircraft handling qualities having major deficiencies (para. 3.3.3.2).
NORMAL OPERATION:	Pilot rating less than 3.5, based on Cooper-Harper scale, indicating aircraft handling qualities with satisfactory characteristics. (para. 3.3.3.2).
OSCILLATORY FAILURE:	An oscillating system response to a faulty signal (para. 3.4.1.4).
PARALLEL ACTIVE:	A redundant actuator configuration with two or more actuators operating simultaneously to drive a common output (para. 2.2.2.2).
PASSIVE FAILURE:	No system response to an input command. This is commonly caused by an open input signal path (para. 3.4.1.4).
PILOT RATING:	See Cooper-Harper.

POSITION SUMMING: A parallel active mechanization where two or more actuators are summed through differential linkage. The output is the sum of the individual actuator output positions (para. 2.2.2.2).

SLOWOVER FAILURE: A system response to an erroneous ramp signal, usually until it reaches a fully extended or retracted position (para. 3.4.1.4).

STEP FAILURE: A system response to an erroneous step signal. The extreme step failure is a hardover failure. (para. 3.4.1.4).

THRESHOLD: The minimum input signal amplitude necessary to produce a measureable change in the output position (fig. 11).

VELOCITY SUMMING: A parallel active mechanization, where two or more actuators are summed through differential gearing. The system output is the sum of the individual actuator output velocities.

-3 dB CUTOFF FREQUENCY: The frequency at which the system amplitude response is down 3 dB.

1.0 INTRODUCTION

Economically and competitively viable commercial aircraft of the future will have to take advantage of all possible gains in aerodynamic efficiency and weight reduction in order to improve fuel utilization, operating costs, and performance. Utilization of advanced technology flight control concepts will significantly contribute to the successful achievement of these gains.

The flight control systems of modern advanced aircraft are necessarily becoming complex and increasingly difficult to design and implement as more demands for added control functions, increased performance and operational capabilities, improved economics, and greater safety reliability and survivability are made. Furthermore, these advanced flight control systems require the integration of complex hydraulic actuators and electronic control systems. These design integrations are not easily realized due to implementation requirements and techniques. The associated implementation problems require careful attention to successfully develop the required advanced technology flight controls for aircraft of the future.

This report presents the results of a quantitative study of two different actuator redundancy mechanization concepts that provide a fail-operational capability suitable for use in flight-critical control applications. This is the final report of Contract NAS2-7966, Mod. No. 3, Redundant Actuator Development Program. This contract study is the second phase of a program at NASA-ARC to develop and broaden the technology base of flight-critical flight control systems for the next generation of advanced technology commercial jet transport aircraft.

Section 2.0 contains a summary of the study's purpose, approach, results, and conclusions, the configurations studied, and recommendations for future developments.

Section 3.0 contains the study's ground rules and requirements. This section also describes the detailed approach and techniques, the detailed test and analysis procedure used, and the design tradeoff studies conducted in arriving at the final actuator configuration definitions. The results of the quantitative study are also contained and presented in this section.

Section 4.0 contains the final definition and specification of the two actuator concepts studied.

Section 5.0 discusses the applicability of the actuation concepts to advanced supersonic transport control systems as well as the applicability to other types of aircraft control systems.

2.0 SUMMARY

2.1 STUDY PURPOSE AND APPROACH

The Boeing Company has completed a study of flight control system redundancy mechanization applicable to aircraft requiring fail-operational control. This report presents the results of a quantitative evaluation of two different actuator redundancy mechanization concepts that provide a fail-operational capability suitable for use in flight-critical control applications.

With the present state-of-the-art in hydraulic and electronic components, adequate safety cannot be guaranteed for flight-critical items on a single-channel basis. Redundancy therefore is required, which leads to additional complexity. The number of redundant channels required depends to a great extent on the method of mechanization.

Two methods of actuator redundancy mechanization representative of those most likely to be used in future airplanes have been studied to provide a quantitative assessment of design application to an Advanced Supersonic Transport (AST) airplane. The two actuator configurations studied were a four-channel, force summed system and a three-channel, active/standby system.

The study approach in producing a quantitative evaluation of the two actuator concepts was to (1) establish allowable actuation system operating characteristics based on a piloted evaluation of airplane handling qualities, (2) determine and evaluate, by analysis, the actuation system operating characteristics and configuration-sensitive parameters, and (3) quantitatively compare the two concepts relative to safety, reliability, maintainability, vulnerability, weight, and cost.

2.2 STUDY BASELINE CONFIGURATION

Producing a quantitative evaluation of alternative actuator concepts necessitated the selection of an appropriate baseline airplane type and configuration, a representative control system configuration, and equivalent actuator system configurations. This section establishes and describes the baseline configurations used in this study.

2.2.1 CONFIGURATION REQUIREMENTS

In the last few years, emphasis in new airplane configurations has mainly been directed towards improving economy and efficiency. Increasing reliability and safety, containing or reducing airfield lengths, enhancing flying qualities, and reducing noise and pollution.

In the past, feedback control systems have been instrumental in improving handling qualities, reliability, and safety. The first applications were in autopilots, implying control of aircraft attitude to relieve the pilot on long stretches. Later, stability augmentation control became widely used, inferring better handling and smoother riding aircraft. More recently, feedback control systems with greater authority have been used to achieve precise control when the pilot could not adequately accomplish the task, such as in landing approach in poor visibility (e.g., autoland control). Although a hardover failure command in a low-authority system can be tolerated since the pilot can override and switch it off, hardovers in large-authority systems can lead to loss of control and catastrophe. It is necessary to safeguard against such failures by multiplexing control channels to identify and override a faulty channel.

An alternate approach to past practices associated with airframe designs is to configure the vehicle to take full advantage of the benefits of *augmentation*. Augmentation, as used in this context, is not restricted only to improvement of handling qualities but includes improvement of a variety of characteristics such as ride qualities, load alleviation, flutter suppression, performance, and any other area in which a benefit can be gained. The basic difference in this approach is that the configuration of the vehicle is dependent on the impact that the control system makes on the design. The flight control system then becomes as important as structure with respect to flight safety, and therefore the matter of system reliability and redundancy are a paramount concern.

2.2.1.1 Airplane Configuration

The purpose of this AST-funded study was to produce a quantitative assessment of the actuation-system design application to an AST airplane. To conduct this study a representative advanced airplane model, the Boeing 2707-300 SST, was selected as the baseline airplane configuration.

The design development of the Boeing 2707-300 SST emphasized the achievement of an optimum configuration arrangement from the standpoint of aerodynamic and structural efficiency. Substantial improvements in weight, drag, and balance resulted from configuring the airplane with the c.g. limit aft of the maneuver-neutral point at subsonic speeds and sizing the longitudinal surface to meet control moment requirements rather than stability requirements. The resulting unstable airplane had to be augmented through the flight control system to provide acceptable handling qualities. This required incorporating a highly reliable stability augmentation system (SAS) that would ensure at least minimum-safe handling qualities. This minimum-safe SAS, being likened to basic structure, became known as Hard SAS or HSAS. The design approach for HSAS was to specify the simplest possible system that could assure at least minimum-safe handling qualities, to take all precautions to optimize the reliability of the system during manufacture and service, and to minimize maintenance requirements.

Normal handling qualities were provided by an outer loop system called an electrical command and stability system (ECSS). This sytem was more complex than HSAS and used more conventional packaging techniques.

Further, it was decided for the prototype SST airplane that when flight safety was dependent on an augmentation system, safety would be ensured by another means, until the reliability of the new design was proven in a true flight environment. This was accomplished on the Boeing prototype SST by providing a mechanical backup control mode.

The concept of dissimilar redundancy is significant in ensuring safety in aircraft control system designs. The more the dissimilarity between alternative means of control, the less the probability of a common failure mode or single failure event destroying all means of control.

2.2.1.2 Flight Control Configuration

The 2707-300 longitudinal control system was selected as the baseline control system for this study. The following considerations were pertinent to selecting the B2707-300 SST pitch axis as the baseline:

1. Considerable effort and development had gone into evolving the B2707-300 airplane and subsystems.

2. The B2707-300 SST is currently mechanized and modeled on the NASA-ARC motion simulator.

3. The actuator study relates directly to the "Handling Qualities" portion of this same contract study since critical flight configurations for the actuation system evaluation study were determined from the handling qualities work.

2.2.1.3 Safety/Reliability Criteria

Safety is the primary purpose of the airworthiness requirement contained in Part 25 of the Federal Aviation Regulations. These requirements must always be kept in mind, as they are the standard by which airworthiness of the aircraft are judged. Besides the FAA regulations, consideration must be given to the requirements imposed by other nations on aircraft offered for sale within their jurisdiction. Among nations having specific airworthiness requirements are the United Kingdom, France, the Netherlands, Germany, Italy and Australia.

Existing regulations (FAR 25.21(e)) recognize that acceptable flight characteristics may depend upon a stability augmentation system or upon other automatic or power-operated systems.

With the present state-of-the-art in hydraulic and electronic components, adequate safety cannot be guaranteed for flight critical items on a single-channel basis. The probability of failure in a critical system must be extremely remote (extremely improbably) inferring that total system failure rate must be less than 1×10^{-9} failures per flight hour. Electrohydraulic systems on a single-channel basis demonstrate 1×10^{-3} to 1×10^{-4} failures per flight-hour which falls far short of this goal. Redundancy, therefore, is required to make up this difference, which leads to additional complexity. The number of redundant channels required depends to a great extent on the techniques of mechanizing the system.

The required level of overall function reliability is achieved in control systems by increasing redundancy for those functions that do not have the desired reliability. For example, controllability of the latest generation of large jet transports is dependent on the integrity of the hydraulically powered controls. Reliability for safety of flight is provided by multiple hydraulic systems. The ultimate levels of reliability are required only for those functions needed for safe termination of flight.

2.2.2 CONFIGURATION CONCEPTS

The flight control systems of modern advanced aricraft are necessarily becoming complex and increasingly difficult to design and implement as more demands are made for added control functions, increased performance and operational capabilities, improved economics, and greater safety and survivability. Future aircraft will have to take advantage of all possible gains in aerodynamic efficiency and weight reduction with their impact on fuel savings, operating costs, and performance improvements to be economically and competitively viable. Advanced control requirements and advanced flight control system concepts, involving complex hydraulic actuators and electronic control systems, are not easily realized due to implementation techniques and associated problems. These problem areas require careful attention in the development of advanced technology flight control and aircraft of the future.

Reliability and safety requirements for flight-critical control systems that convert and amplify flight control and stability augmentation commands to provide inputs to the control surface power actuators are determined by the need to remain operational in spite of control channel malfunctions. Actuation systems with fault-corrective capability to meet the reliability requirements and satisfy FAA regulations require at least four active channels or three monitored channels. Although the minimum redundancy level for flight-critical surface power actuators is three, surface power actuators could be mechanized with the higher level of redundancy.

To meet these levels of reliability, special consideration must be given to the control system design. Such considerations include design simplification, derating of components, elimination of electrical connectors, and physical isolation of electrical wiring and hydraulic power. Even then, redundancy is usually required to obtain satisfactory reliability from the complex hydraulic actuators and electronic control systems used in airplane flight controls.

Use of redundancy to achieve reliability has always been an accepted engineering design technique. However, the advantages of redundancy are not easily realized in control systems because of signal channel interaction, failure effects, performance degradation after failures, null shift with channel switching, and failure detection problems. These problem areas with redundant control systems and actuators require careful attention in system design and mechanization.

2.2.2.1 Redundancy Requirements

Redundancy requirements for flight control actuation systems can be divided into two areas, the requirement for flutter-free control surfaces, and the requirement for operative flight-critical control surfaces.

The need to minimize airplane weight reduces the permissible use of control-surface mass balance as a means of preventing control-surface flutter. If mass balance is not used, the surface must be restrained by the surface control system. The Federal Aviation Regulations, volume III, part 25, paragraph 25.629, "Flutter deformation, and fail-safe criteria", requires that an airplane be free from flutter after any single failure in the flight control system, plus any other *reasonably probable* single failure or malfunction affecting flutter. Hydraulic system failures are classified as reasonably probable by the FAA. Therefore, when the airplane design dictates that control surfaces be restrained by the surface power actuators to avoid the mass balance weight penalty, at least two surface power actuators and three hydraulic systems for each surface are required.

Independent of considerations for suppression of surface flutter, surface power actuator redundancy is influenced by the need to maintain control of the airplane flight path. The Federal Aviation Regulations, volume III, part 25, paragraph 25.671, requires that the airplane must be capable of safe flight and landing after any single failure, excluding jamming, in combination with any probable hydraulic or electrical system failure.

One form of redundancy to assure continuance of a control function after failures would be to use multiple-control surface segments, independently controlled, in each airplane axis. Control-surface redundancy, when used for failure tolerance reasons, requires surface oversizing so that the total authority exceeds the minimum requirement by some margin. Otherwise, the whole philosophy of multiple surfaces is invalid. If actuator redundancy were not required for prevention of flutter, each surface could be controlled by a single actuator. Degraded, but safe, operation could be possible if one or more surface segments became inoperative. This concept is used in some current airplanes. However, if the airplane design is such that a limited number of flight control surfaces are available or if all control surfaces in an axis are needed for flight path control, each surface must remain operative and controllable after certain dual-control system failures.

Advanced supersonic cruise transport airplanes will probably be limited in the use of control surface redundancy, particularly in the longitudinal axis, because of the need to attain maximum aerodynamic efficiency. The need for minimum weight in an advanced supersonic transport airplane will also limit the consideration of mass balance for flutter prevention. These two factors are sufficient to set the minimum redundancy level for surface power actuators and show the need for redundancy in flight control actuation systems.

The general approach to implementing a fail-operational control system is to use redundant channels and to have a way of rejecting erroneous outputs. The problems of developing fail-operational control systems can be separated into two interelated areas: (1) design of the method for selecting an output from the redundant channels, and (2) design of the method for detecting and deactivating a failed channel.

2.2.2.2 Actuation Redundancy

There are two distinct types of actuator redundancy used in aircraft control systems. One type is the parallel-active configuration (fig. 1). The parallel-active configuration incorporates multiple channels which perform identical control functions simultaneously. The other type is the active/standby configuration (fig. 2), which incorporates multiple channels, only one of which controls the output of the system at any one time. The principal differences between the two types are as follows:

- The parallel-active technique requires the redundant control channels to be working together at some point in the control system. Hence, the failure of one of the control channels can cause an output performance change. For an active/standby system, the control channels operate independently and failures of the active control channel cause transfer to a correctly operating standby channel with no performance degradation.

- The parallel-active system requires all of the control channels to be working at the same time. The failure of one channel is compensated for by the remaining correctly operating channels (to varying degrees). Therefore, it is not necessary to immediately deactivate the failed channel. In an active/standby system, rapid transfer between control channels is essential (with the actual required transfer time determined by the particular application).

There are three options available in the mechanization of parallel-active actuator systems. The control channels can be brought together and the actuator outputs summed by (1) force summing, (2) velocity summing, or (3) position summing (fig. 1).

Force summing is the most common technique used in mechanizing parallel active systems. By force voting several actuators on a common output, an output representing the mid-value of all input commands can be achieved. One problem with this type of system that does not exist with other types is the force fight that can occur between actuator channels when channels differ in input command or actuator characteristics.

Velocity summing is an alternate parallel-active mechanization which does not incur the force fight problems of the force summed systems. The best example of this mechanization uses servo motors summed through differential gear boxes. Net output velocity is the sum of the individual motor velocities and the force output is equal to the individual force outputs of the servo motors.

Position summing systems have no actuator force fight. However, since the individual actuators are summed through differential linkages, a channel failure or actuator shutdown will reduce total output stroke capability. Each individual actuator must have a larger stroke than the minimum allowable output stroke to accommodate channel failures. This characteristic restricts the application of the position summing technique to systems that require only small displacement. It has been used in dual systems for series actuation. Mechanization becomes difficult when more than two actuators are summed because of mechanism complexity.

2.2.2.3 Implementation Factors

There are several factors that must be considered when redundant actuators are used. The most significant are those that affect normal operation, affect operation after failures, and cause interface problems. These are failure insensitivity, failure monitoring, load sharing, and input mismatch.

Failure Insensitivity.—Failure insensitivity is the ability of a redundant control system to experience failures and automatically continue operation with an acceptable transient. If the system performs a critical function, operation must be maintained (be fail-operational) in the presence of one or more failures. However, a fail-operational system does not ensure minimum control-system transients. The criticality of transients has an effect on the detail design of the system. All the methods of redundancy mechanization previously discussed can be fail-operational. However, the number of channels required and the failure characteristics vary as in the following discussion.

1. Fail-operational capability can be achieved in parallel-active systems by majority voting or averaging three or more active actuators. With three active channels, operation continues after the first failure. With four channels, operation continues after two failures, if the first failed channel has been deactivated before the second channel fails. In the force-voted systems a failed channel is automatically overpowered by the remaining channels and the magnitude of the failure transient can be insignificant. Displacement and velocity summing provide an averaged output but have inherent failure transients and steady state null offsets after failures. The magnitudes of the transients are dependent on the system's closed loop response.

2. Active/standby systems require a failure detection system to assess that the active channel has failed, automatically disconnect it, and switch to a good channel. The failure transient is dependent upon the failure detection level, the switching time, and the tracking of the standby channel.

Failure Monitoring.—Detection and indication of failures during operation must be provided so that failed channels or actuators can be deactivated to preserve the integrity of the system. The failure detection system must be designed to detect all types of failures; hardover, passive, oscillatory, and slowover or ramp which could produce an unsafe situation.

The ability of the failure detection system to sort out legitimate failures from apparent failures that might occur due to adverse tolerances has an equivalence in reliability. If the failure detection system trips a channel off inadvertently due to an apparent failure, the equivalent mean-time-between-failure (MTBF) for the system may be significantly affected.

Failures in parallel-active systems may be sensed by in-line monitoring of actuator characteristics or by cross-channel monitoring between active acuators. A method of reducing the number of redundant actuators is to use a model of a working channel for cross-channel monitoring. While this extends the system's fail-operational capability with one less working channel, its effectiveness depends on how well the model matches the actual hardware. In certain applications, where actuators are large and where weight is critical, the model approach may provide a way to minimize overall weight.

In active/standby systems each channel must be individually monitored for failure detection. Each control channel is usually duplicated or modeled to provide the comparison required to detect a failure of the active channel.

Load Sharing.—Load sharing is a measure of the ability of multiple actuators with identical inputs to work together in positioning a common output. Load sharing is a problem peculiar to force summed actuators since, obviously there is no force fighting in an active/standby system with only one channel controlling at a time, or in position summed and rate summed systems where forces of individual actuator channels are additive.

Ideally, it is desirable that the load be divided equally among redundant actuators to eliminate any force fighting. However, tracking errors arise due to tolerance buildup in each actuator servo loop and actuator installation that tend to make each actuator seek a unique position, even though the input commands are identical. With the actuators tied to a common output all position commands will not be simultaneously satisfied and force fights will occur between actuators.

To minimize the force fighting in force summed actuator configurations and assure acceptable sharing of the load, four methods are commonly used.

1. Accurate tolerance control of the actuator feedback loop: A mechanical actuator can be mechanized with good tolerance control because of the manufacturing accuracies that are possible and the unchanging nature of the mechanical linkages. In contrast, an electrically controlled actuator has command path elements such as summing amplifiers, demodulators, and feedback transducers which can change characteristics with time, temperature, and power. It is generally accepted that the tolerances associated with an electrically controlled actuator are significantly greater than for a mechanically controlled actuator.

2. Compliance between channels: In some applications the structural compliance between actuators allows sufficient individual actuator position difference to reduce force fights through the normal position feedback loop.

3. Low force gain actuators: Low pressure gain servovalves can be used to reduce the force fight resulting from expected valve command differences to an acceptable level. In some applications a feedback path consisting of deflections of the actuators' reaction structure is sufficient to provide the actuator force gain reduction, and reduced force fight. Another way to reduce actuator force gain is to use actuator load pressure as a feedback command. However, there is a limit to the amount of compliance that can be tolerated without reducing the overall actuator stiffness below a minimum allowable level. Reducing actuator force gain (stiffness) has been used successfully where inputs are reasonably matched, such as multiple surface power actuators signalled by a common mechanical command, or secondary actuators where the output load is small.

4. Equalization to average load: For cases where the actuators are required to operate into large aerodynamic loads and have uncontrolled input mismatch, any pressure feedback system requires modification to be useful. The individual actuator load must be compared to the average load. Computation of the average load and the individual difference from average requires cross-channel comparison. This method does not degrade actuator stiffness but adds complexity and introduces the possibility of cross-channel failures.

Input Mismatch.—Differences in commands (input mismatch) due to tolerances in the electrical control system, from sensor to actuator, can be quite high. As much as a quarter of full-scale command can result unless some design precautions are taken to prevent such buildup. It should be noted that differences in commands generated by actuator loop tolerances are generally an order of magnitude less than those generated by computational elements in the upstream portions of the system. The various methods of redundant actuator mechanization that deal with the input mismatch problem are as follows.

1. Force summing systems: In force summing systems, the output is the mid value of all input commands. The force fight that occurs due to input command mismatch can be reduced by the same methods used to insure load sharing. In some applications the only possible means of controlling input command differences may be through the use of electronic signal command conditioning.

2. Velocity summing systems: Velocity summed actuators allow the individual channels to cancel command differences by differentially summing rates.

3. Position summing systems: Position summed actuators accommodate command differences by producing a single output which is the average of the input commands.

4. Active/standby systems: Usually the active actuator is commanded by a single electronic channel and mismatch is no concern during operation. Mismatches between the commands of the active and the standby channel are of concern, however, and must be minimized to avoid large transients upon switching from active to standby actuators.

2.2.2.4 System Mechanization Concepts

The concept of using multiple channels of similar control information is generally applied by utilizing some form of summing or decision process prior to the control surface, thus bringing the various signal paths together to form a common command. Surface actuator input signals can be either electrical or mechanical, or both.

The power levels associated with the electronic signals for fly-by-wire command, autopilot, and stability augmentation systems are kept at low levels as a matter of good design. These low-level signals are required to command surface actuators that operate at high power levels. To transform the low-level electrical commands to surface displacements controlled by large hydraulic power actuators requires signal conversion and amplification. This is normally achieved using small electrically signalled hydraulic servo actuators as one of the stages of amplification to form a mechanical consolidation prior to the surface power actuators. These small actuators are termed secondary actuators (figs. 3 and 4).

It is advantageous to treat the command computation and signalling errors independently from the power actuation errors through the use of the secondary actuator. Some of the advantages are:

- The secondary actuator can become a synchronizing stage between the two functions by providing a single-valued mechanical command.

- Although secondary actuators do not eliminate the problems of redundant actuators, the magnitude of the problems are less severe because the secondary actuators operate at significantly lower force levels than the surface power actuators.

- When surface power actuators are isolated from the upstream command differences, the task of providing adequate power actuator load sharing becomes easier, permitting a simpler and more reliable mechanization.

A major concern in developing a system concept is determining the best way to interface the system components and control modes. One of the more important decisions in establishing the skeleton of the actuation system concept is to determine how the mechanical control path and the redundant electronic control paths are to be mechanized.

Considerable trade studies for this design decision were made during the Boeing B2707-300 SST development. In considering all the disadvantages and advantages of the alternative schemes, a summing interface method was selected. Although more complex, the summing interface allowed continued control of the surface through the mechanical path if a jam occurs in the secondary actuator output mechanism (fig. 3).

The summing concept requires a centering detent (to ground) to ensure adequate control of the surface actuation system via the mechanical backup control after complete loss of electrical control. These detent springs can be either engaged continuously or engaged only after an electrical or hydraulic failure has occurred in a channel. If engaged continuously, the detents would act like nuisance loads to the secondary actuators in normal operation. At the expense of a slight increase in complexity, the detent springs could be caged (locked out) in normal operation, and then engaged only after a failure in that channel. This latter approach has the advantage of eliminating the unwanted detent loads from normal operation. This latter mechanization approach was selected for this study.

2.2.2.5 Actuation System Concept Selection

Four types of actuator redundancy have been discussed, i.e., force summed, velocity summed, position summed, and active/standby. The benefits of using secondary actuators as a means of signal conversion, signal amplification, and command path synchronization to control the surface power control actuators have been discussed. Surface power actuators are usually force summed mechanical input actuators. The system differences are in the redundancy mechanization of the secondary actuators.

Although the use of velocity summing solves the problem of force fight there are disadvantages which make this type of system a questionable candidate for future use in critical flight control applications on civil aircraft. The complex gearing could make it difficult to prove that jam-type failures would be extremely remote, as required by FAA regulations. Also, for the same output force the electromechanical actuator is larger and heavier than an equivalent electrohydraulic actuator.

Position summed systems are difficult to mechanize for more than two redundant channels because of the complex linkage required. In addition, the loss of rate and travel capability after failure and the inherent output position transient that occurs with failure are disadvantages.

The active/standby and the force summed systems have advantages and disadvantages that must be considered in conjunction with the specific airplane and control system application.

Of the options discussed, initial studies under contract NAS2-7653, Redundant Actuator Development Study (phase I), disqualified all but the force summed approach of the parallel-active actuator systems and the active/standby approach for continued study.

The study reported in this document, under contract NAS2-7966, concentrates on evaluating two secondary actuator mechanizations (force summed and active/standby). A quantitative evaluation was made of these two mechanization concepts to determine their operational and performance characteristics for normal conditions, for failure conditions, and for variations in critical design parameters. The two actuation concepts studied are shown schematically in figures 5 and 6. Functional diagrams of these concepts are shown in figures 7 and 8. Functional descriptions, referring to these figures, of the concepts are presented in paragraph 2.4.1.

2.3 PILOTED SIMULATION EVALUATION (FSAA)

A piloted motion simulator study was conducted on the flight simulator for advanced aircraft (FSAA) at NASA-ARC. This piloted simulator study evaluated the interaction of pilot, airplane, and control system. The purpose of this evaluation was to establish and define the allowable limits of critical actuation system design parameters.

This section describes the baseline airplane and control system models used and the study approach taken, and summarizes the major results and conclusions of the simulation study. A more detailed presentation of the scope, background, test conditions, and study results is contained in paragraph 3.3.

2.3.1 BASELINE AIRPLANE CONFIGURATION

The B2707-300 supersonic transport airplane was selected as the baseline airplane configuration for this study. The four flight configurations selected as representative of the B2707-300 flight envelope, and utilized as the test flight conditions during the FSAA testing are listed as follows.

1. High speed cruise within normal operation boundary

2. High speed cruise within minimum-safe operation boundary

3. Landing approach within normal operation boundary

4. Landing approach within minimum-safe operation boundary.

2.3.2 BASELINE CONTROL SYSTEM CONFIGURATION

The B2707-300 longitudinal control system was selected as the baseline control system for this actuation study.

This system is shown functionally in its entirety in figures 9 and 10, and represents the system used in conducting the piloted simulation study. The secondary actuator (EC Servo) functional block on these figures was modified consistent with the study.

The EC servo model was expanded sufficiently to represent the secondary actuator system parameters critical to the definition and development of the secondary actuator concepts under study. This model did not represent a specific secondary actuator configuration. Rather, it consisted of linear filters, limiters, and time-dependent functions to allow simulation of the secondary actuator characteristics of importance to this study. As such, limitations on specific parameters were established to correlate with the Boeing based (analog) simulation to produce a quantitative evaluation of the candidate actuator concepts being studied.

Figure 11 shows a functional diagram of the EC servo used in the study. The system was built around the existing EC servo model as indicated in the figure and was represented as single channel.

2.3.3 STUDY REQUIREMENTS AND APPROACH

The objective of this evaluation study was to establish design criteria for the secondary actuation system applicable to an AST flight-critical control system. These criteria were established based on pilot evaluation of manually flying a simulated supersonic transport airplane. A piloted motion simulation, using the FSAA at Ames, was used to investigate and evaluate various secondary actuator parameter effects on airplane handling quality characteristics.

The simulation study was organized and planned to produce (1) a control transient evaluation to relate actuator transient variations with pilot rating, (2) a design parameter evaluation to relate actuator performance variations with pilot rating, and (3) a determination of the allowable limits of critical actuation system design parameters.

The testing performed on the FSAA simulator was divided into two categories. The first category evaluated the effects of different control system failure modes on airplane handling qualities. The second category investigated the effects of variations of actuator design parameters on airplane handling qualities. Each test category was evaluated at the four flight conditions described in paragraph 2.3.1 which included operation at landing approach and high speed cruise. The airplane configurations were chosen so that the handling qualities bordered on the lower limits of normal and minimum-safe operation. At each combination of airplane configuration and flight condition a test sequence was performed with changing actuator characteristics, until clear trends in pilot ratings were established.

The detailed test and evaluation procedures are presented and discussed in paragraph 3.3.

The handling qualities criteria used in evaluating the results of the piloted simulation tests are as follows:

1. With the airplane in a normal handling qualities state (i.e., $PR \leqslant 3.5$), the airplane handling qualities shall not degrade below a PR of 3.5 following a single probable control system failure, and a PR of 6.5 following a second control system failure (i.e., a probable failure plus any other failure).

2. With the airplane in a nominal minimum-safe handling qualities state (i.e., $4.5 < PR < 6.5$) and with a normal flight control system (i.e., no flight control system failures), the airplane handling qualities following a single control system failure shall not degrade below a PR of 7.

The method by which these criteria were applied to the test data is shown in figure 12.

2.3.4 MAJOR RESULTS AND CONCLUSIONS

The test results of the FSAA evaluation are summarized in tables 1 and 2. Table 1 presents the failure transient test results summary and table 2 presents the actuator design parameter variations test results summary.

These tables contain data showing the maximum magnitude of allowable surface transients for various types of failure modes and the maximum magnitude of allowable actuator system nonlinearities. These data have been established from the pilot evaluation results contained in figures 13 through 25 using the criteria of figure 12. Two sets of data are shown in both table 1 and 2, one for the high-speed cruise flight condition and one for the landing approach flight condition. Typically, at these two flight conditions the airplane was evaluated at two levels of handling qualities; i.e., normal-operation handling qualities and minimum-safe handling qualities. For the normal-operation handling qualities airplane, two allowables are shown; i.e., for a first system failure and for a subsequent (second) system failure. For the minimum-safe handling qualities airplane, only a first failure allowable was established and is shown.

Table 1 contains the summary of allowable failure transients for step, oscillatory (for constant frequency and for constant amplitude), and switching delay failure types. The values shown in the table are horizontal stabilizer deflection angle in degrees.

Table 2 contains the summary of the maximum allowable magnitudes of actuator system nonlinearities; specifically deadband, hysteresis, and threshold. Similar to table 1, the allowable magnitudes shown are horizontal stabilizer deflection angle in degrees.

Figures 13 through 25 present the test data. These figures contain data plotted as pilot rating (PR) versus either failure transient amplitude or actuator parameter variation. The figures are further categorized in relation to flight conditions and airplane handling qualities.

Actuator step failures were found to be most critical during cruise. This is evident in figure 13 where pilot rating appears very sensitive to step amplitude. At the high dynamic pressure associated with supersonic cruise, control sensitivity becomes large, resulting in large load factor increments for small stabilizer surface deflections. Upsets caused by sudden changes in stabilizer angle resulted in prolonged load factor oscillations.

During landing approach (fig. 14) step inputs proved most critical when they occurred immediately prior to or during landing flare and in the wrong direction, that is, nose down.

An oscillatory failure at constant frequency, ω = 1 Hz, appeared to be a nuisance failure rather than serious hazard to the safety of the airplane (figs. 15 and 16). Although it rapidly degraded the normal handling qualities characteristics of the airplane, large amplitudes (of 50% of maximum stabilizer deflection) were required before the handling qualities were forced beyond the criteria limits. The cause of this is believed to be filtering effects that the airplane inherently has at this frequency.

The second sequence of oscillatory failures evaluated the effects of frequency variation. In figures 17 and 18 it is obvious that the airplane-pilot combination was extremely sensitive to frequencies in the range of 0.1 Hz to 0.5 Hz. This observation would dictate that failures within these boundaries should be avoided for all failure modes.

The switching delay tests were conducted to assess the effect of switching from an active to a standby channel in an active/standby secondary actuator system. These tests were run only at a landing approach flight condition. As is evident in figure 19, the airplane would sustain large switching delays before handling qualities boundaries were exceeded.

Figures 20 through 25 contain the test results of the actuator design parameter testing.

The test results indicate that the airplane configuration having baseline minimum-safe handling qualities generally appears more sensitive to variations in parameter magnitude than does the configuration having baseline normal handling qualities. The one exception to this observation is shown in figure 20. Also, the airplane displays greater sensitivity to parameter variations at high-speed cruise than it does for low-speed operations, such as landing approach.

Figures 20 and 21 show the effect of deadband. The high speed cruise data of figure 20 show a greater sensitivity to deadband than the landing approach data of figure 21. Furthermore, contrary to a general trend, the high-speed cruise normal-operation airplane was more sensitive to deadband than was the minimum-safe handling qualities airplane.

Figures 22 and 23 show the effect of hysteresis. The normal-operation airplane at high-speed cruise and landing approach had about the same sensitivity to variations in hysteresis. However, the minimum-safe high-speed flight condition was considerably more sensitive than the minimum-safe landing approach flight condition.

Figures 24 and 25 show the effect of threshold. Both the minimum-safe and normal-operation airplane had similar trends with the high-speed cruise flight condition being more sensitive to variations in threshold than the landing approach flight condition.

2.4 ACTUATION CONCEPT COMPARISON EVALUATION

The two actuator concepts were developed and evaluated to produce a quantitative comparison. Included in this section are detailed descriptions of the concepts, requirements and study approach of the comparison evaluation study, and major results and conclusions of this study phase. A more detailed presentation of the trade study is included in paragraph 3.4.

The active/standby and the force summed systems have advantages and disadvantages that must be considered in conjunction with the specific airplane and control system application. The most significant differences between the two types of mechanization are in the following areas.

Normal Performance.—The single channel operation of the active/standby system can give optimum performance. In the force summed system, residual actuator force fight can affect output resolution and reduce actuator stiffness.

Failure Transients.—The force summed system can be mechanized to give very small failure transients. The active/standby system design must trade failure detection levels and nuisance trips against allowable failure transients.

Performance After Failure.—The active/standby system preserves normal performance in the failure sequence from the active channel to the standby channel and on to the second standby channel. The force summed system suffers a performance degradation as channel failures occur. This degradation can be exhibited as reduced resolution capability and force output.

Failure Monitoring.—The active/standby system requires immediate failure detection to be safe following failures. Consequently, each standby channel in the active/standby system must be continually monitored to assure that it is capable of control if the active channel fails. Furthermore, somewhere in the system a device like a switch or blocking valve is required to provide a successful transfer to a standby channel, upon detection of a malfunctioning active channel. The force summed system does not require immediate detection of a failure to be safe. The force summed system utilizes only active channels continually monitoring each other and requires no immediate switching to be safe. Failure detection is only required to enable a failed channel to be shut down before another failure occurs.

2.4.1 CONCEPT DESCRIPTIONS

2.4.1.1 Active/Standby Description

The active/standby configuration incorporates multiple channels, only one of which controls the output of the system at any one time. To provide dual fail-operative performance; i.e., continue operation after sustaining two failures, the active/standby system redundancy level is triple channel. This is accomplished by making each control channel essentially dual; an actuator channel and a model channel. The monitoring system compares the actuator channel with the model channel, and, if a disagreement exists, that control channel is deactivated. Using this form of in-line monitoring keeps the redundant control channel separate with a minimum of inter-channel connection.

The control channels operate independently and failures of the active control channel cause transfer to a correctly operating standby control channel with no performance degradation. Because the standby control channels are not load sharing, they cannot oppose a failure in the active control channel. Therefore, rapid failure detection and transfer between control channels is essential to accomplish fail-operational performance.

Referring to figures 5 and 7, each actuation channel, denoted by A, B, and C, is connected to the common output. One channel, at a time, is activated to become the active channel by deactivating its bypass valve. Deactivating a bypass valve allows that actuator to produce an output force and thereby allowing it to control the output. Simultaneously, the bypass valves on the standby channels are activated to bypass their respective actuators, thus preventing the standby channels from controlling the output.

Once a channel is activated, then an input command, denoted by subscript c, to the servo summing amplifier produces an error signal to the servo valve. The servo valve responds to produce a hydraulic flow to cause the actuator piston to move. This movement is sensed electrically by an LVDT (linear variable differential transformer) to provide position feedback through the feedback electronics to the servo amplifier to close the position loop.

Failure detection of an active channel is accomplished with a model channel that monitors the actuation channel. A servo amplifier, servo valve, position LVDT, feedback electronics, and a differential pressure transducer make up the monitor channel system. The amount of mistrack between the actuator channel and the model channel is measured as a servo valve Δp signal. If this signal becomes excessive, the failure detection logic is activated to bypass that active channel and to switch a standby channel to become a new active channel.

2.4.1.2 Force Summed Description

The parallel-active, force summed configuration incorporates multiple channels which perform identical control functions simultaneously. The parallel-active system requires all of the control channels to be working at the same time and working together at some point in the control system.

Fail-operational capability can be achieved by majority voting three or more active actuators. Dual fail-operative performance is provided with four channels, if the first failed channel has been deactivated before the second channel fails. A failed channel in the force summed system is automatically overpowered by the remaining channels and the magnitude of the failure transient is minimized. The failure of one channel is compensated for by the remaining correctly operating channels (to varying degrees). Hence, the failure of one of the control channels can cause an output performance change. However, it is not necessary to immediately deactivate the failed channel.

Referring to figures 6 and 8, each of the four actuation channels (A, B, C, and D) is connected to the common output. Each actuator channel is activated by operating its bypass valve to *not* bypass, thereby allowing that actuator to produce an output force. In normal operation, all four channels are activated to function together. Once an actuator channel is activated, an input command to the servo amplifier produces a signal to the servo valve which, in turn, produces a hydraulic flow to cause the actuator piston to move. This movement is sensed by an LVDT to provide an electrical feedback signal through the feedback electronics to the servo amplifier to close the position loop. Should all four channels not go to exactly the same output position, each of the actuator channels will oppose the others. In doing so, the attempt to produce an output position causes a differential pressure to build up within the actuator.

Electrical and mechanical unbalances between the four servo channels are corrected by feeding back to the position loop, a signal proportional to the valve Δp. This signal is shown integrated electronically and fed back to provide the necessary steady-state balancing input. These signals are also fed through a failure logic, such that if the signals exceed a specified magnitude for a certain period of time, a channel failure is indicated, and that channel is deactivated. Operation continues on the remaining channels.

2.4.2 STUDY REQUIREMENTS AND APPROACH

The objective of the concept comparison study was to produce a quantitative evaluation of the two selected actuation configurations. The general approach taken was to conduct an extensive simulation study using an analog computer, and to conduct various analytical trade studies.

The analog simulation study was used to develop the detail mechanization definition of both actuator concepts, to evaluate their operational and performance characteristics, and to determine the sensitivity of design parameter variations on their operation.

Performance criteria used in the analog simulation study were frequency response, transient response, resolution, and failure transients.

Performance characteristics for each criterion were determined for normal operation and for failed channel(s) operation.

Analog simulator tests were also conducted to determine the sensitivity of varying these actuator design parameters: valve pressure and valve flow gain, valve flow limit, system backlash, actuator friction and damping, actuator rod spring, and actuator dynamic spring.

The effect of parameter variations were determined by evaluating changes in performance characteristics.

The analog study was divided into a configuration definition phase and an evaluation phase. In the first phase, each secondary servo actuator concept was analyzed to determine the effect on system performance and failure detection capability when using a single-stage or two-stage servo valve. During this phase, failure detection thresholds and time delays were established to minimize failure transients during failure conditions and to avoid nuisance failures during normal operation. During the second phase, performance under normal operating conditions and under failure conditions were evaluated. Similarly, each system's sensitivity to design parameter variations was evaluated.

The analytical trade studies compared the two actuator concepts relative to safety reliability, malfunction reliability, survivability/vulnerability, and system implementation.

2.4.3 MAJOR RESULTS AND CONCLUSIONS

Performance characteristics of both the active/standby and the force summed systems are summarized in figures 26, 27, and 28.

The frequency response plots on figure 26 show that the force summed system has a better frequency response characteristic than the active/standby system. This is attributed to the greater force capability of the force summed system. For normal operation, the force summed system had four times the force capability of the active/standby system.

After a channel failure was detected and disengaged, the force summed system's frequency response characteristics were degraded. Furthermore, the steady-state output was reduced due to the added detent load as channels were disengaged.

The active/standby system showed no loss in frequency response after switching from an active to a standby channel, since a standby channel has the same performance capability when activated.

Figure 27 depicts the transient response characteristics of the active/standby system and the force summed system (normal operation, one disengaged channel, and two disengaged channels). Under normal conditions both systems displayed very similar transient response characteristics. However, upon channel failure detection and disengagement, the force summed system showed a degraded transient response characteristic caused by the centering detent spring that is engaged to the system output upon channel disengagement. The centering detent spring always forces the position output towards null. Thus, whenever the command is away from null, the centering detent acts to retard that motion. For commands toward null, the centering detent acts to enhance that motion. No similar centering detent spring is engaged in the active/standby system. Therefore, no similar performance degradation was observed with the active/standby.

Resolution data for the two systems are presented in figure 28. For normal operating conditions, the force summed system had better resolution characteristics (less hysteresis loss) than the active/standby system. This is attributed to the greater force capability of the force summed system. However, channel disengagements degraded the force summed resolution characteristics, but did not affect the active/standby system.

The force summed system resolution data also showed an output versus input gain reduction about null for one and two channel failures. The reason for this gain reduction about null is the system centering detents that are added as channels are disengaged. These absorb some of the system force capability. However, when the actuation system overcomes the maximum detent force level, the output to input gain returns to normal.

Figures 29 and 30 summarize the comparison of the active/standby and force summed failure transients due to slowover, high gain, passive, step, and oscillatory failures.

No oscillatory failure monitoring system was modeled for either system. However, under certain conditions, an oscillatory failure was detected as a slowover failure.

Generally, the active/standby system experienced larger failure transients than the forced summed system. The failure transient due to a faulty force summed channel was attenuated by the remaining good channels and was limited in magnitude by the failure detection threshold. The active/standby failure transient was not attenuated, although it was limited in magnitude by its failure detection threshold.

The data analyzed to evaluate the relative (active/standby and force summed) system sensitivities to variations in actuator design parameters are summarized in figure 31. This figure shows that the parameter valve pressure gain, valve flow limit, and actuator dynamic spring have no, or relatively insignificant, effect on actuation system performance. Figure 31 also shows that valve flow gain, system backlash, actuator friction, damping, and actuator rod spring are the design parameters having the greatest effect on actuation system performance.

As a result of the studies conducted, the two actuator concepts were evaluated and ranked relative to each other. The ranking of the two concepts based on the selected criteria is presented in table 3. These criteria are not weighted and only a qualitative comparison is stated (i.e., better or worse). The quantitative data substantiating table 3 are contained in paragraph 3.4.

The comparison indicates that the force summed concept better meets performance requirements than does the active/standby. However, the active/standby is superior in meeting reliability, maintainability, survivability, weight, and cost requirements.

2.5 CONCLUSIONS AND RECOMMENDATIONS

The Boeing Company has completed a study of flight control system redundancy mechanization applicable to aircraft requiring fail-operational control systems.

Two methods of actuator redundancy mechanization representative of those most likely to be used in future airplanes have been studied to provide a quantitative assessment of design application to an AST airplane. The two actuator configurations are a four-channel, force summed system, and a three-channel, active/standby system.

As a result of the studies conducted, the two actuator concepts were evaluated and ranked relative to each other. The comparison indicates that the force summed concept better meets performance requirements than does the active/standby. However, the active/standby is superior in meeting requirements of reliability, maintainability, survivability, weight, and cost. Based on these observations, the force summed, secondary actuator system would be the most likely candidate at this time, for an AST application.

In other aircraft applications, where stability augmentation control requirements are less severe and actuator system performance requirements are less stringent, the active/standby system would be a strong candidate.

The actuator configurations were developed in as generalized a form as practical to obtain the basic knowledge and experience of the operational performance characteristics of the two concepts.

Actuator math models of the two configurations were developed and simulated on an analog computer. This simulation study provided the following:

1. A detail definition of the configurations and component mechanization
2. An evaluation of failure detection implementation methods
3. An evaluation of normal operational performance
4. An evaluation of performance over a wide range of failures
5. A determination of actuator configuration sensitive parameters
6. A determination of critical actuator system parameters pertinent to the piloted motion simulation study task

Safety reliability, maintainability, vulnerability, weight, and cost were assessed to aid in establishing a mechanization preference, in addition to defining the detailed mechanizations of the two concepts and determining and comparing their operational and performance characteristics.

Acceptable control system performance is determined by the airplane stability and control characteristics consistent with the mission requirements. The failure-corrective characteristics of an actuation system are the performance characteristics that the control system exhibits when going from one operating mode to another as a result of a component or channel failure; these are as important as the performance characteristics in each failure mode. The general criteria developed in this study relative to acceptable performance degradation and failure transient characteristics for the secondary actuation system were based on pilot ratings of airplane handling qualities. The interaction of the pilot and airplane response with redundant control system designs is important because of performance changes and control transients that occur with failures or actuation shutdown. A piloted motion simulation using the FSAA at Ames was used to investigate and evaluate these effects. No criteria were established relative to augmentation or autopilot control requirements. The piloted simulation study provided the following:

1. A control transient evaluation to relate actuator transient variations with pilot rating
2. A design parameter evaluation to relate actuator performance variations with pilot rating
3. A determination of the allowable limits of critical actuation system design parameters

Future advanced airplane configurations are expected to include major design changes in order to achieve important desired benefits. Some of these recognized benefits are improved airplane performance and utilization, improved costs, maintainability, and survivability, design flexibility, precision control and optimum reponse.

Advanced flight control technology will play an important part in the successful accomplishment of producing these benefits. The significant payoff of advanced control approaches is in the selection of the initial aircraft configuration through an aircraft design approach which permits full tradeoffs between aerodynamics, structures, and controls.

In the commercial market, aircraft utilization is becoming more and more significant. Airline economics are affected by schedule reliability which, in turn, is related to such factors as air space and terminal-area congestion, and weather. The impact of all-weather operation is exemplified by the installation of automatic landing systems as basic equipment on the lastest generation of commercial aircraft. Automatic landing system requirements have had a significant impact on the resulting flight control system configuration. The changing air traffic control environment will undoubtedly have a similar impact on the system design resulting in a requirement for more automation in the flight controls area.

Clearly, safety must not be compromised. When relying on the control system for basic flight safety at all times, a complete failure is intolerable. Sufficient redundancy must therefore be built into all sections of the control system and power supplies to ensure survival in the event of local failures and to reduce the risk of total failure to a very low level.

Design freedom should be maintained to allow practical use of current technology in whatever combinations best satisfy the specific requirements, provided that sufficient confidence has been established in the technology to warrant its use. However, the point at which new technology has been sufficiently demonstrated for reasonable technical and cost risk is often a difficult question to answer.

There is considerable planning underway to work on active control design procedures and applications to provide a comprehensive base for applying active controls to future civil aircraft designs.

The successful demonstration of any of the advanced control concepts is heavily dependent on the associated control system and its mechanization. Since computation and actuation systems are key elements of any control system, the promise of advanced controls will not be realized until the technology for providing the required reliability with acceptable system cost is in hand. Therefore, it is of utmost importance to ensure that the control system design capability is available to allow the utilization of advanced control concepts in the next generation of commercial transports.

The conclusions reached in this study indicate a continued need for research and development of flight critical, secondary actuator systems. Specifically:

1. Develop the true active/standby concept to a hybridized active/on-line concept.

2. Develop detail hardware design definitions of the force summed, active/standby, and hybridized active/on-line actuator concepts.

3. Develop detail definitions of failure monitoring systems for these same actuator concepts.

4. Develop the electronic and mechanical interfaces and evaluate their mutual effects for these same actuator concepts.

5. After developing these first four items, quantitatively determine the advantages and disadvantages of the three actuator concepts.

6. Based on the results of item five, fabricate and test the appropriate actuator concepts in a mini-rig suitable for interfacing with a piloted simulator, like the FSAA at NASA-ARC.

7. Conduct a piloted simulation evaluation with the actual actuator hardware interfaced with a simulated advanced flight-critical, airplane control application.

8. Fabricate and test flight worthy, redundant secondary actuator hardware.

9. Demonstrate and evaluate flight worthiness of flight-critical, redundant secondary actuator mechanizations in a flight test program.

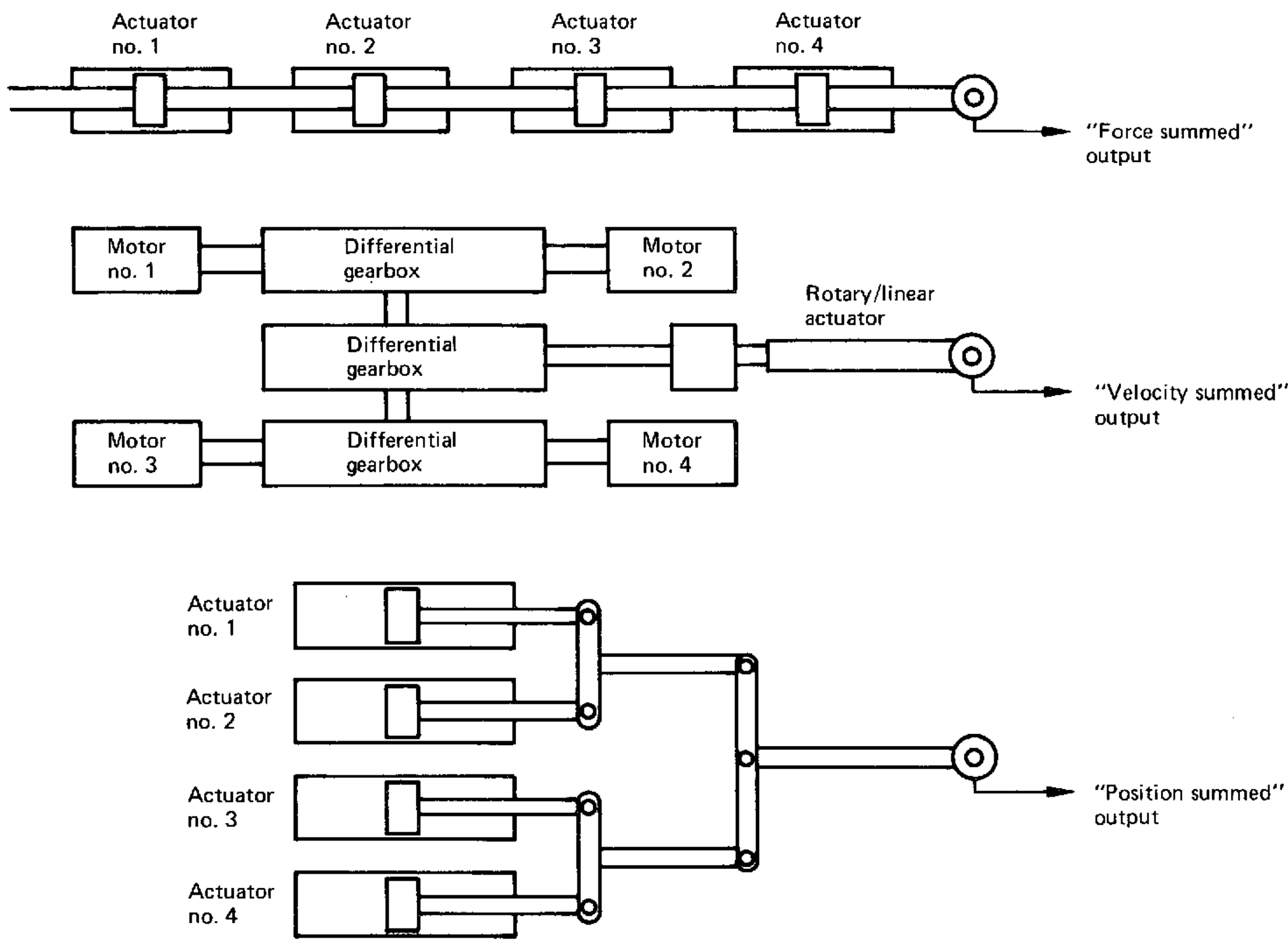


Figure 1.—Parallel/Active Mechanizations

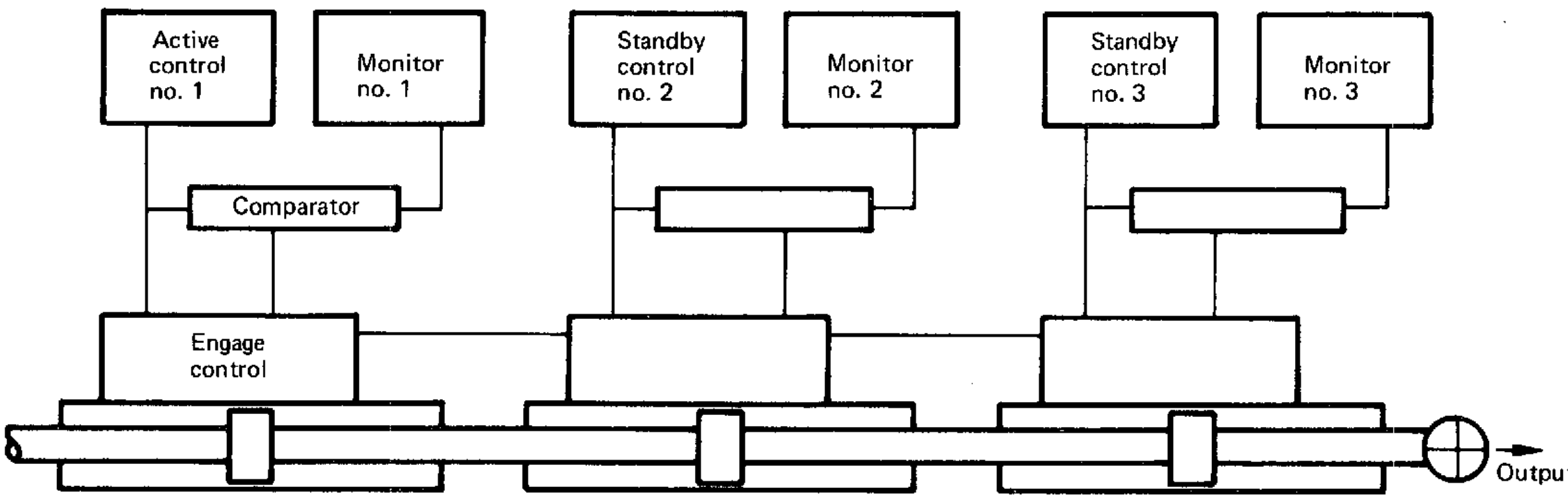


Figure 2.—Active/Standby Mechanization

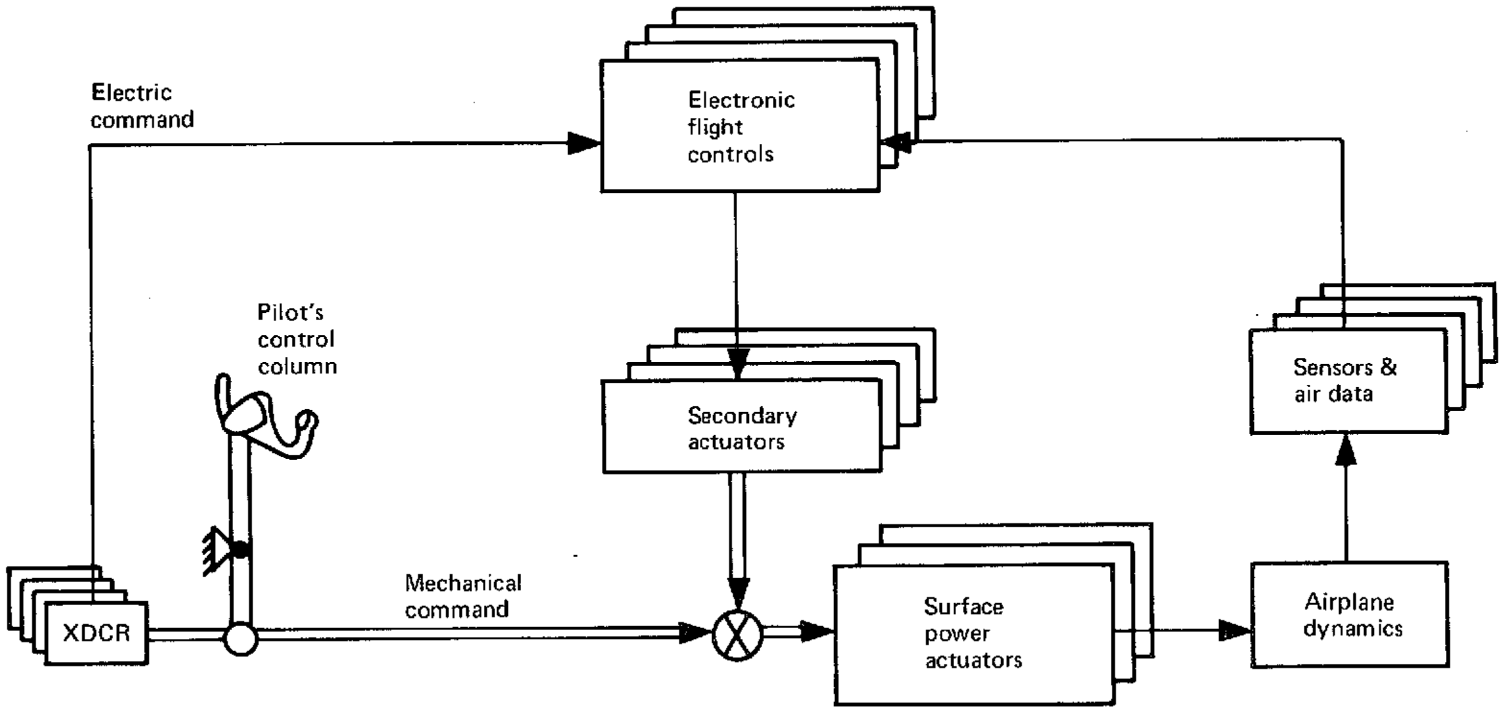
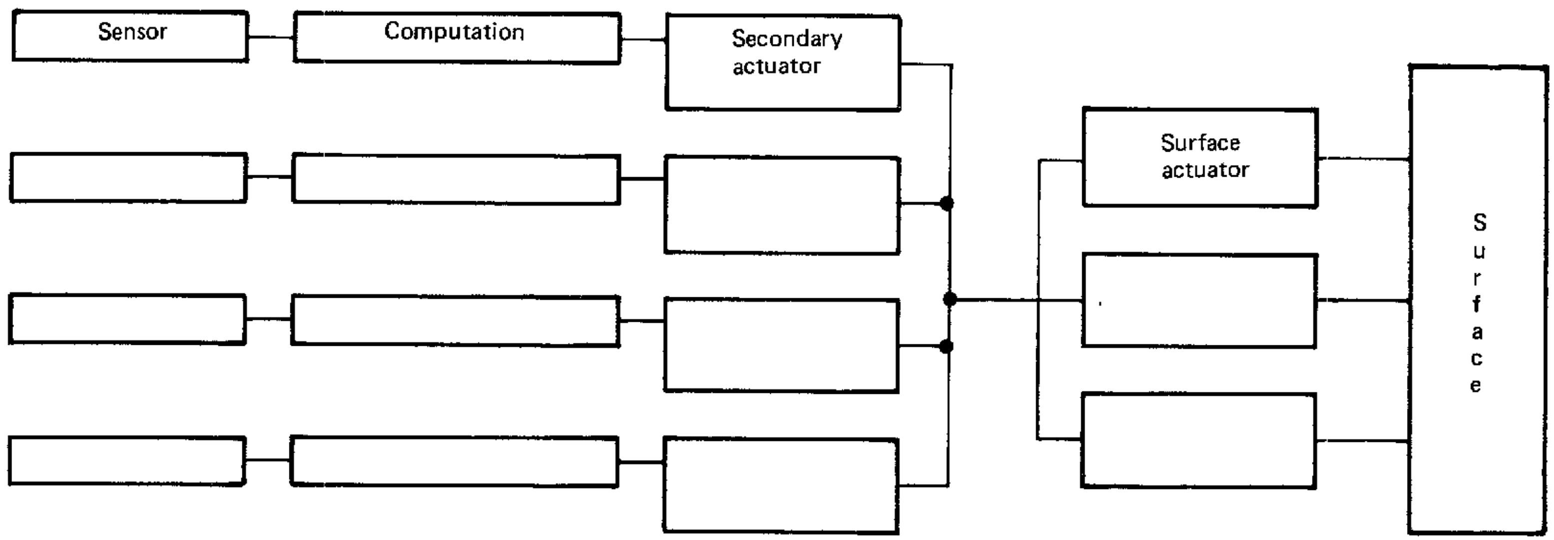


Figure 3.—Control System Schematic



(Typical flight critical electric command)

Advantages:

- Interfaces 4 electronics to 3 power actuators
- Intermediate signal power amplification
- Redundancy management problems treated at lower force levels
- Single valued command to surface actuators
- Surface power actuators isolated from upstream command anomalies
- Permits simpler and more reliable surface power actuator mechanization

Figure 4.—Secondary Actuators

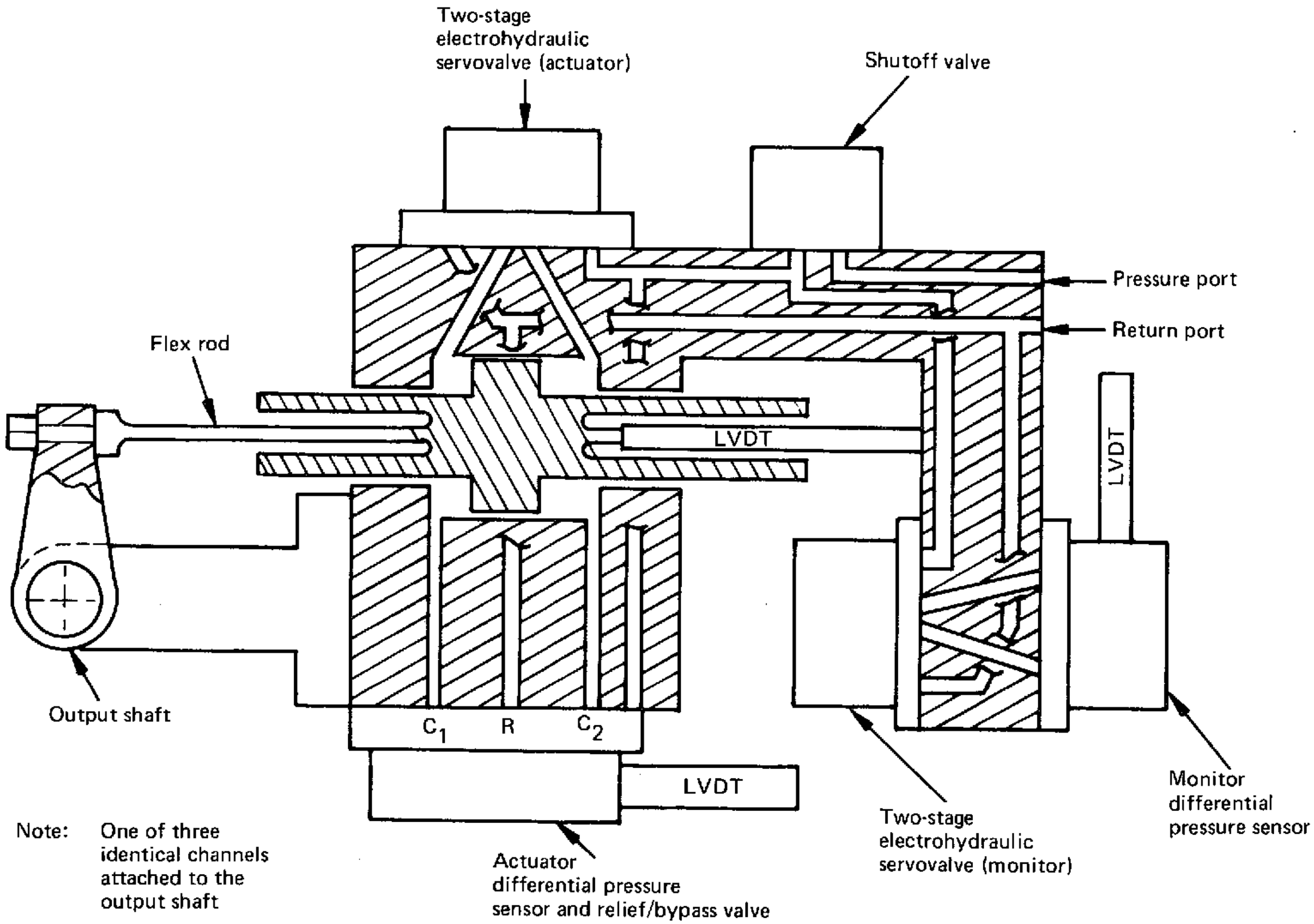


Figure 5.—Active/Standby Actuator, Single Actuator Element

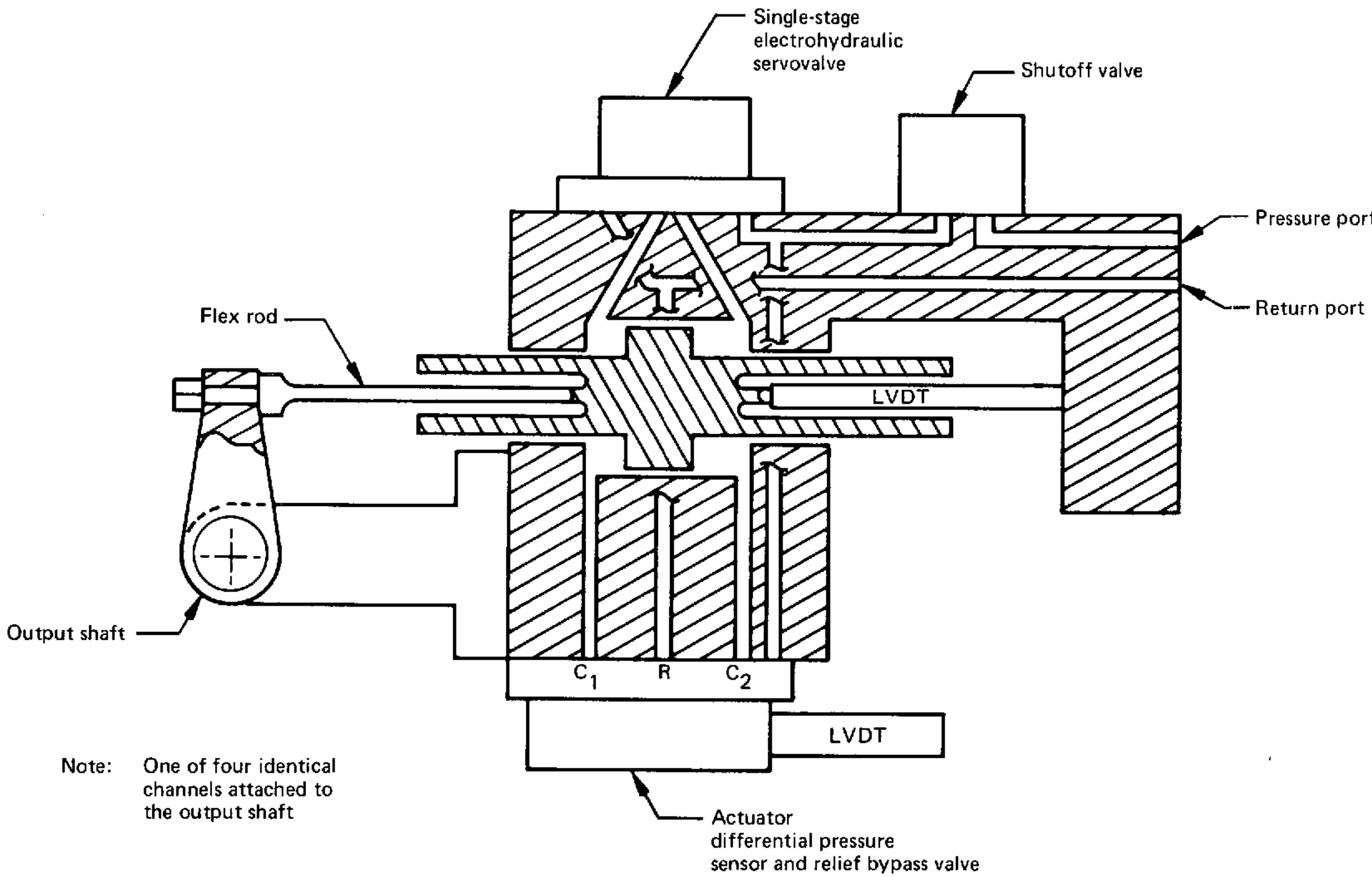


Figure 6.—Force-Summed Actuator, Single Actuator Element

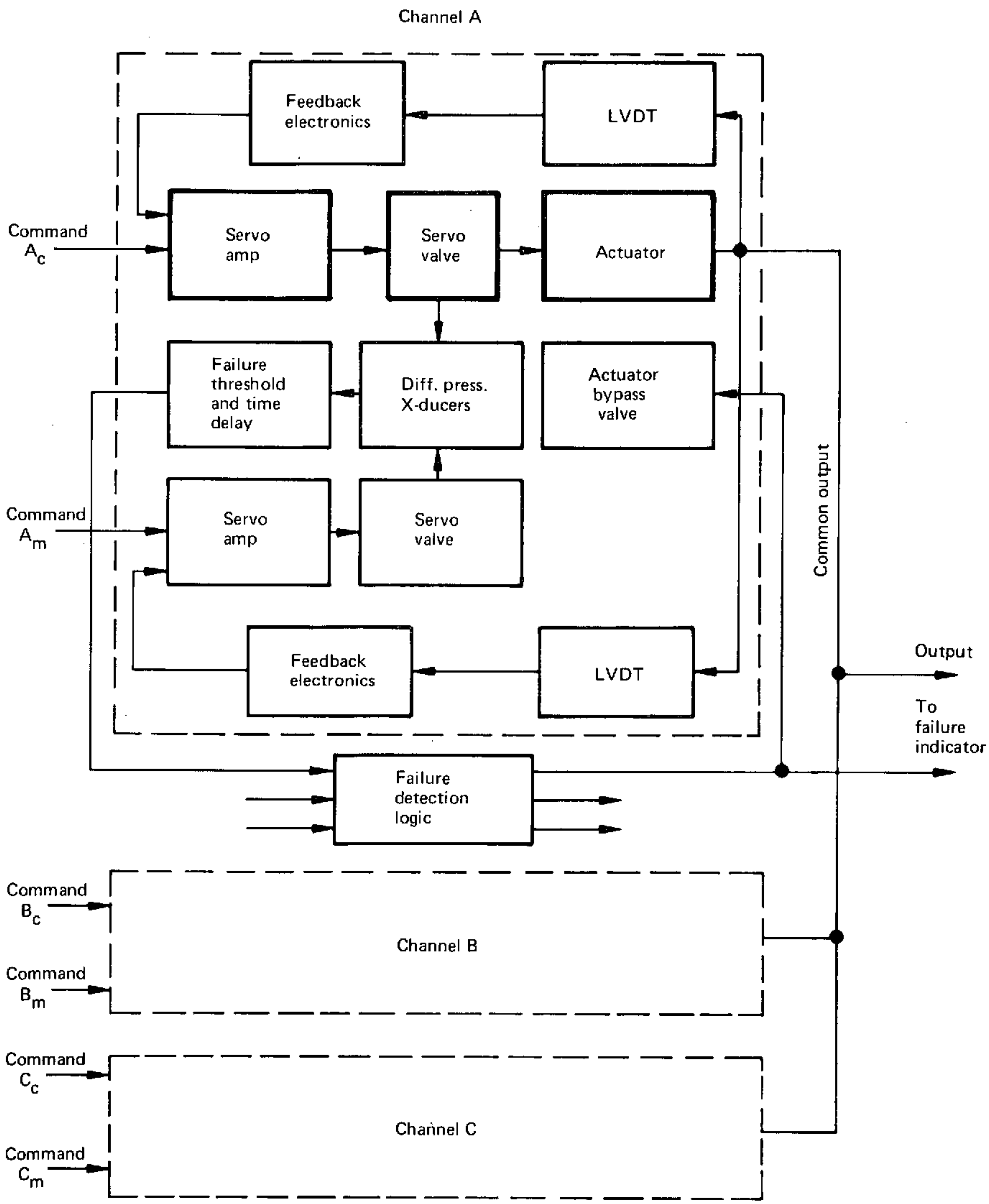


Figure 7.—Triple Channel, Active/Standby, Secondary Actuator Functional Diagram

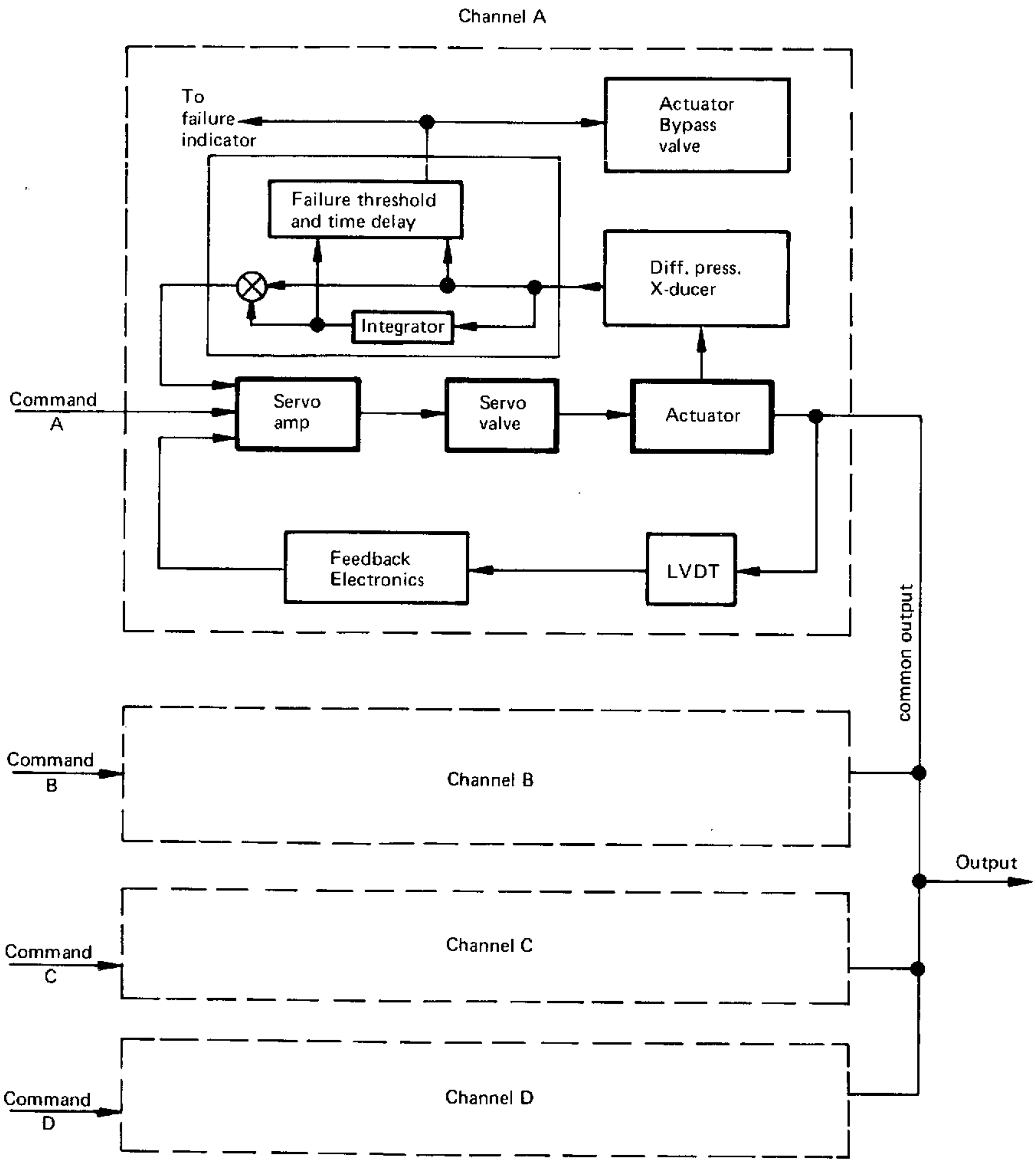


Figure 8.—Quad Channel, Force Summed, Secondary Actuator Functional Diagram

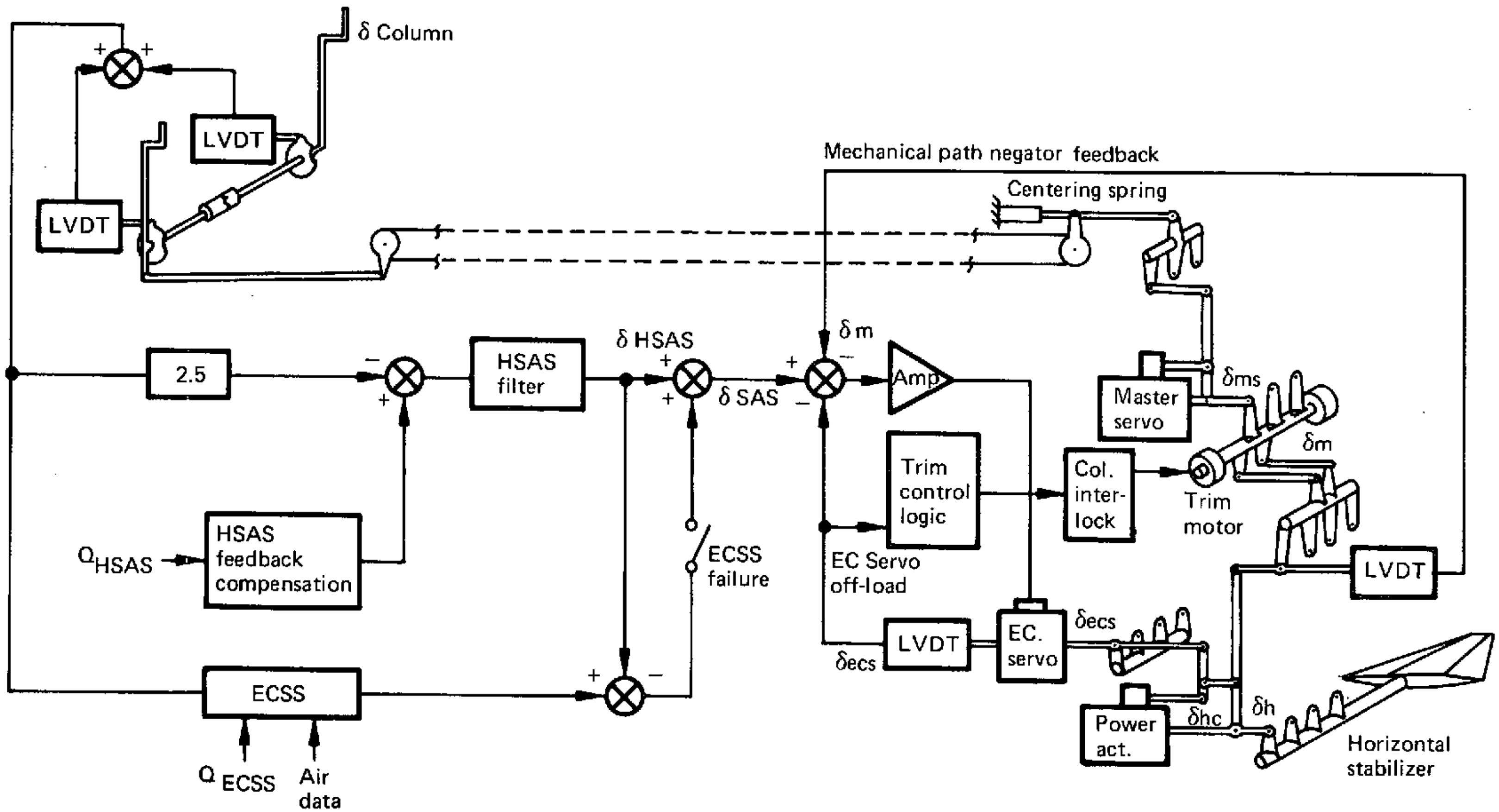


Figure 9.—B2707-300 Longitudinal Control Actuation System Schematic

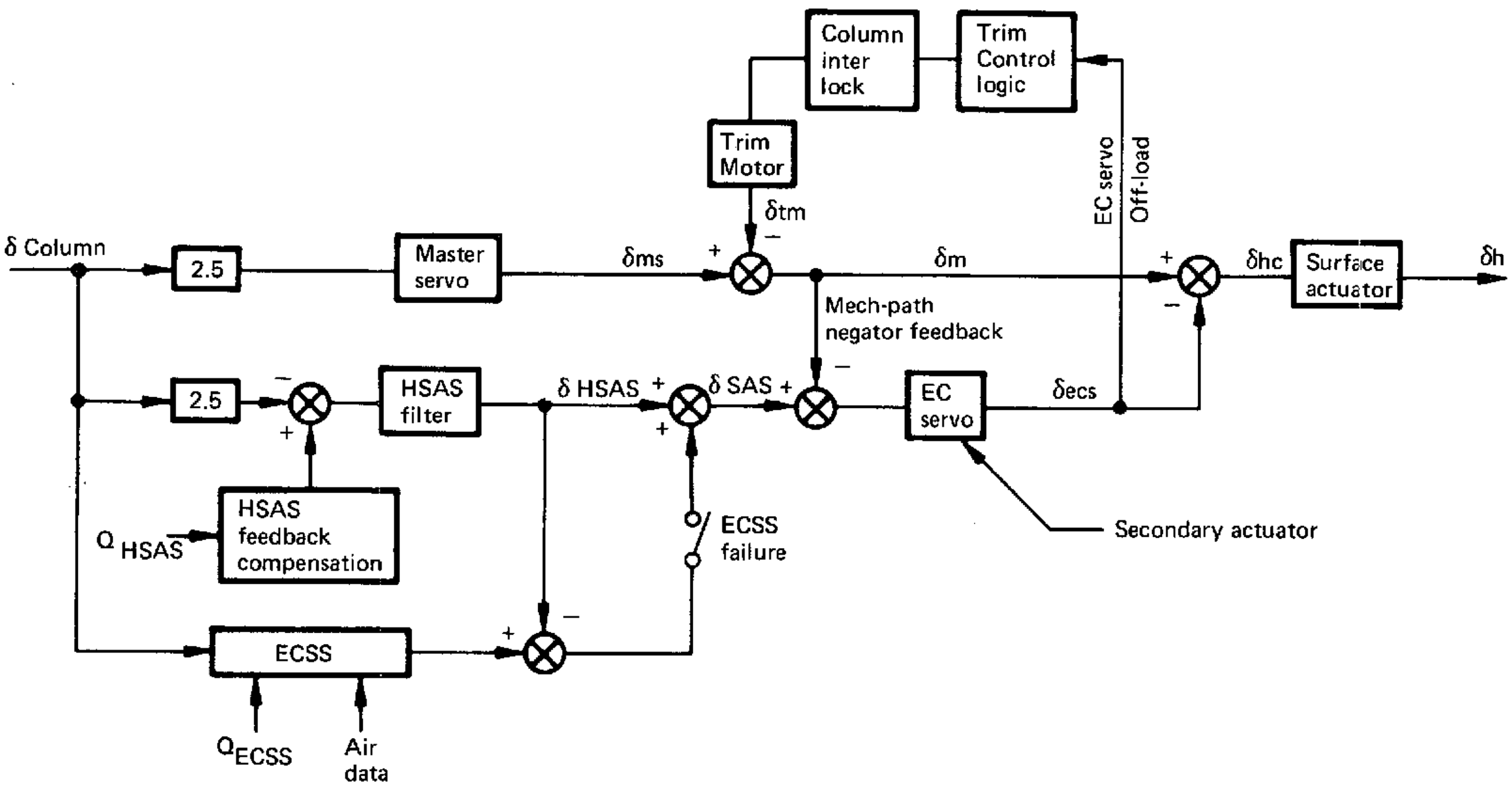


Figure 10.—Block Diagram, B2707-300 Longitudinal Control System

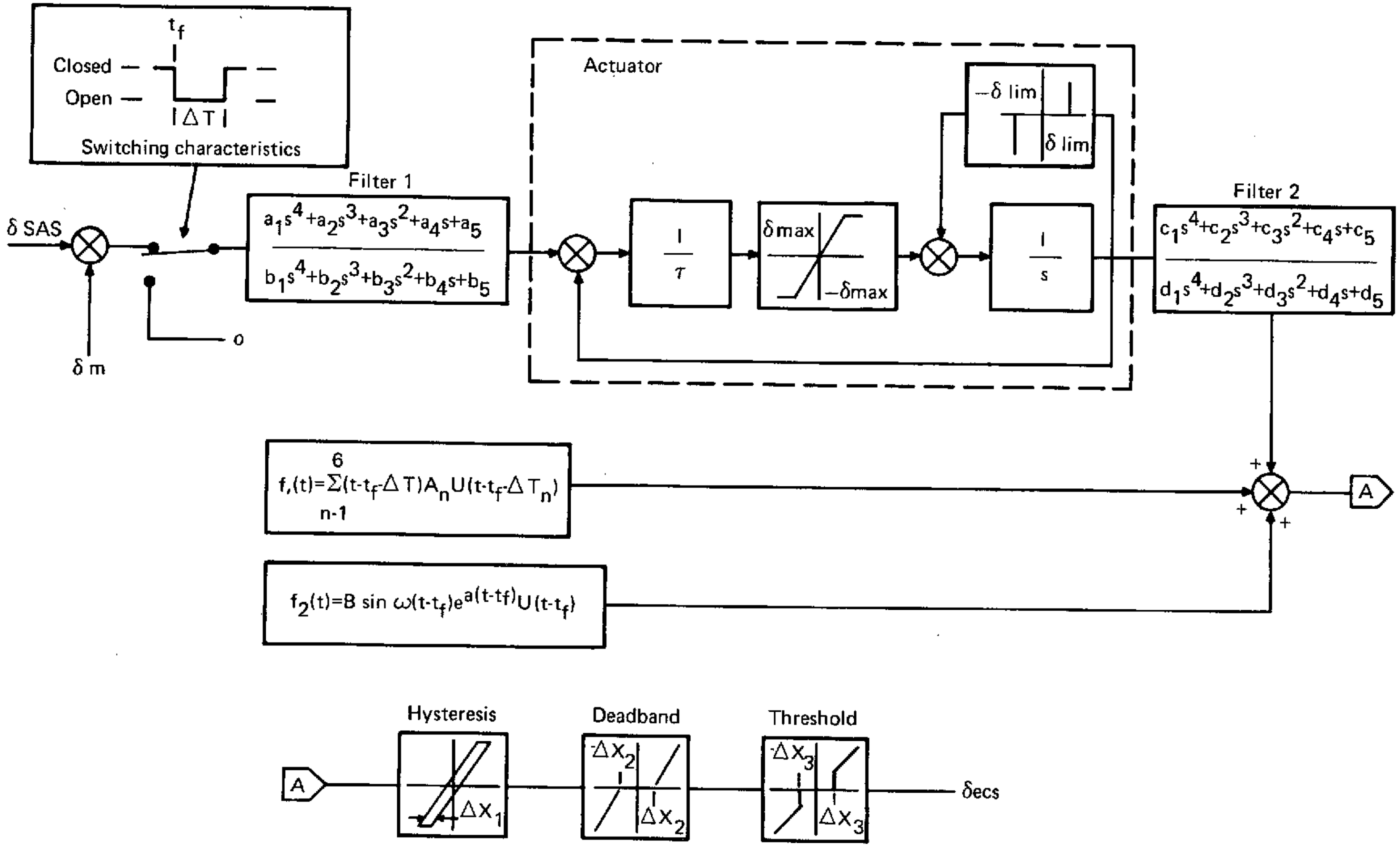


Figure 11.—Secondary Actuator (E.C. Servo) Functional Diagram

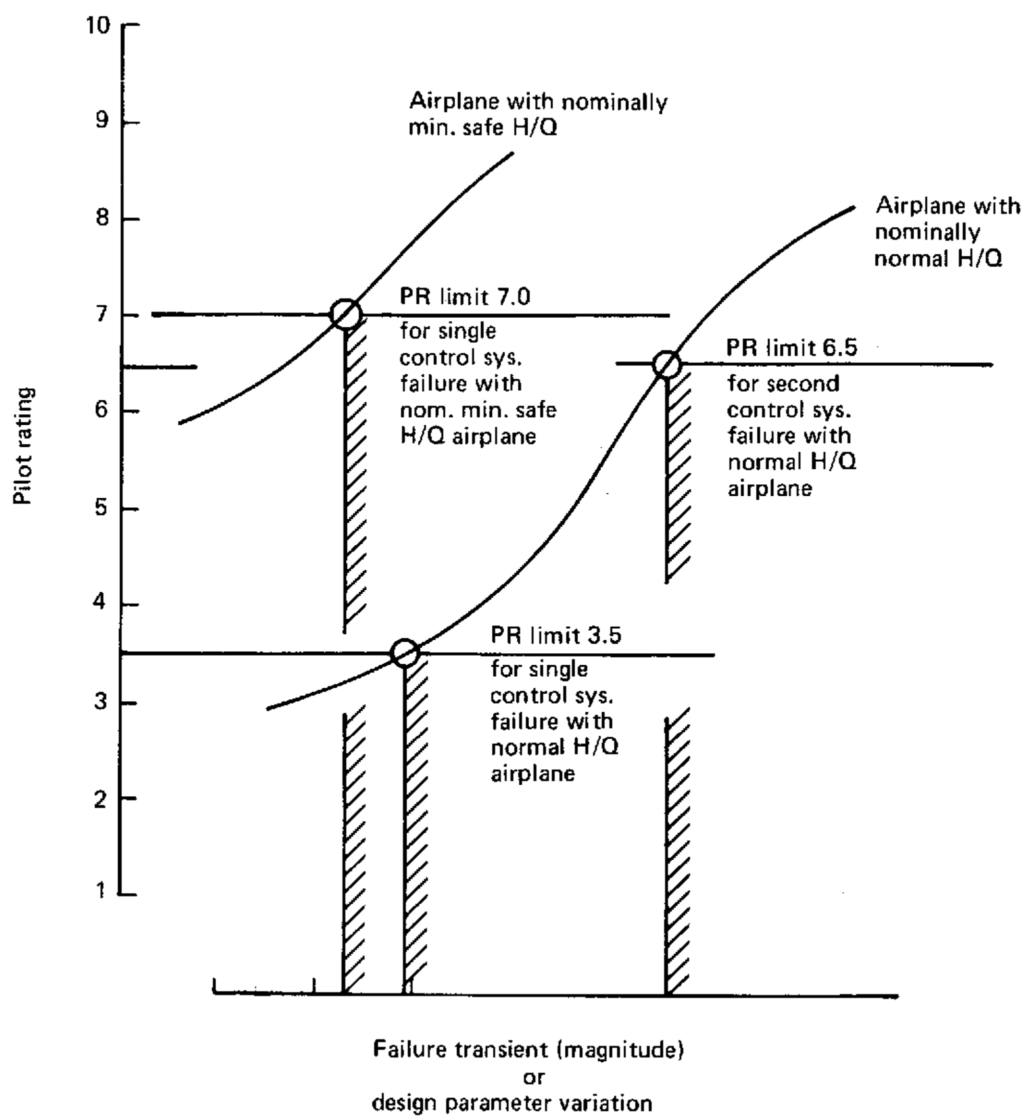


Figure 12.—Evaluation Criteria FSAA Simulation Tests

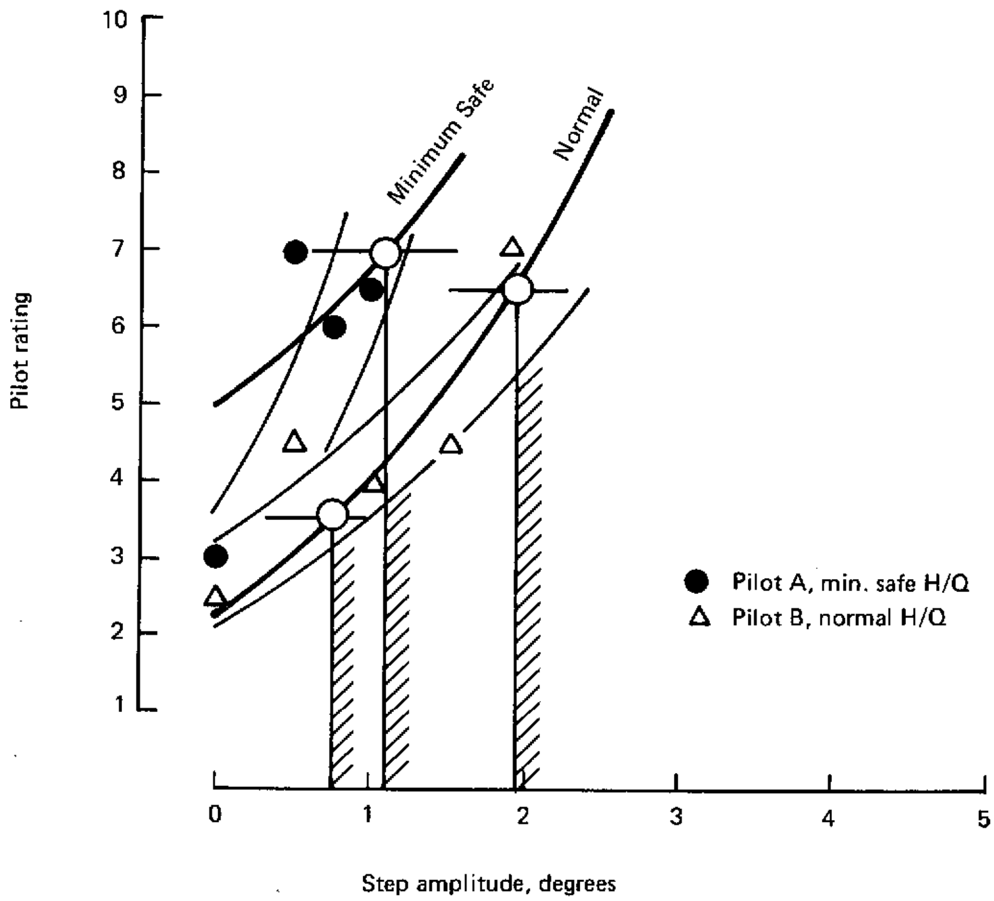


Figure 13.—High-Speed Cruise Step Input Sensitivity

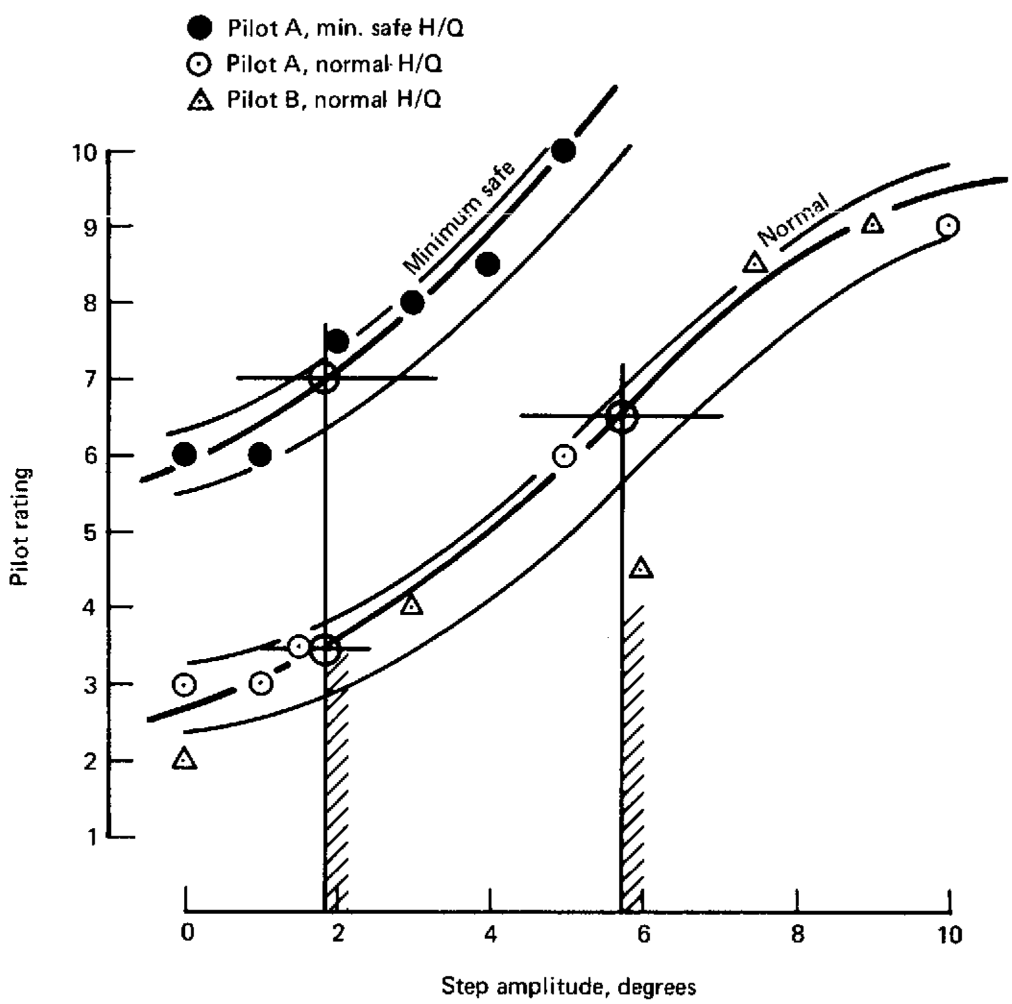


Figure 14.—Landing Approach Step Input Sensitivity

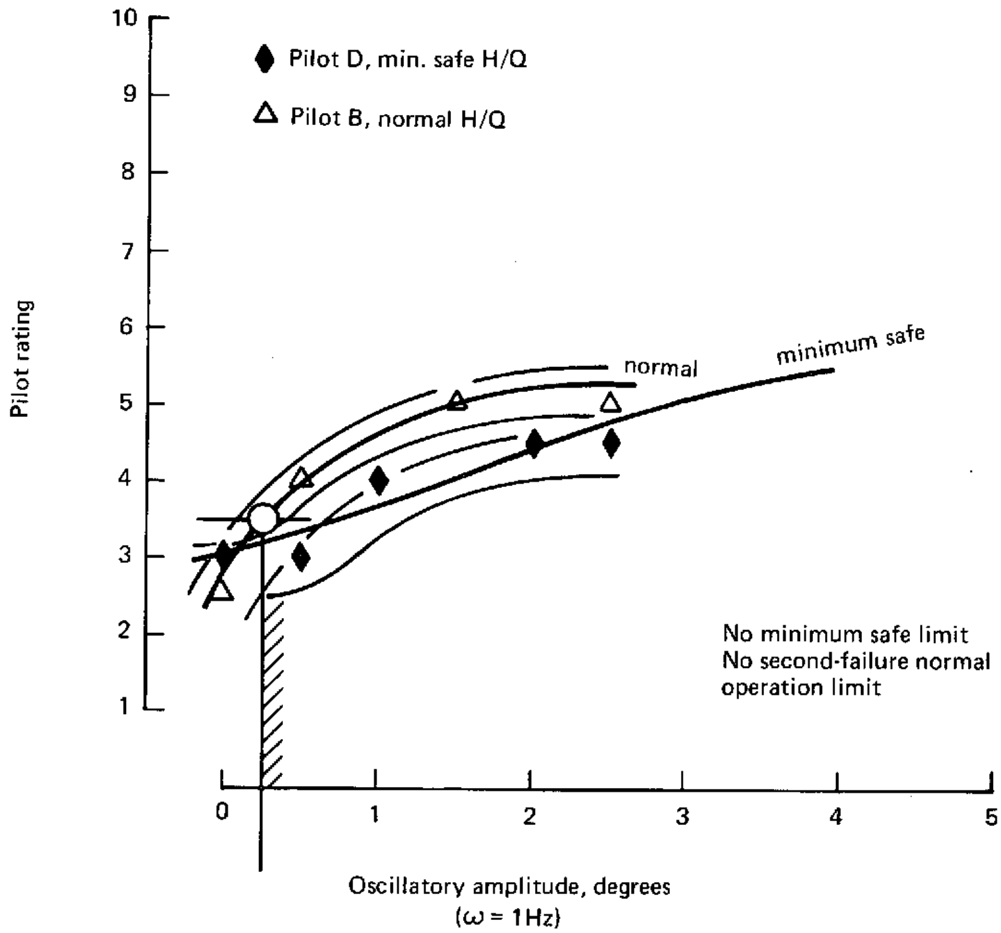


Figure 15.—High Speed Cruise, Oscillatory Amplitude Sensitivity

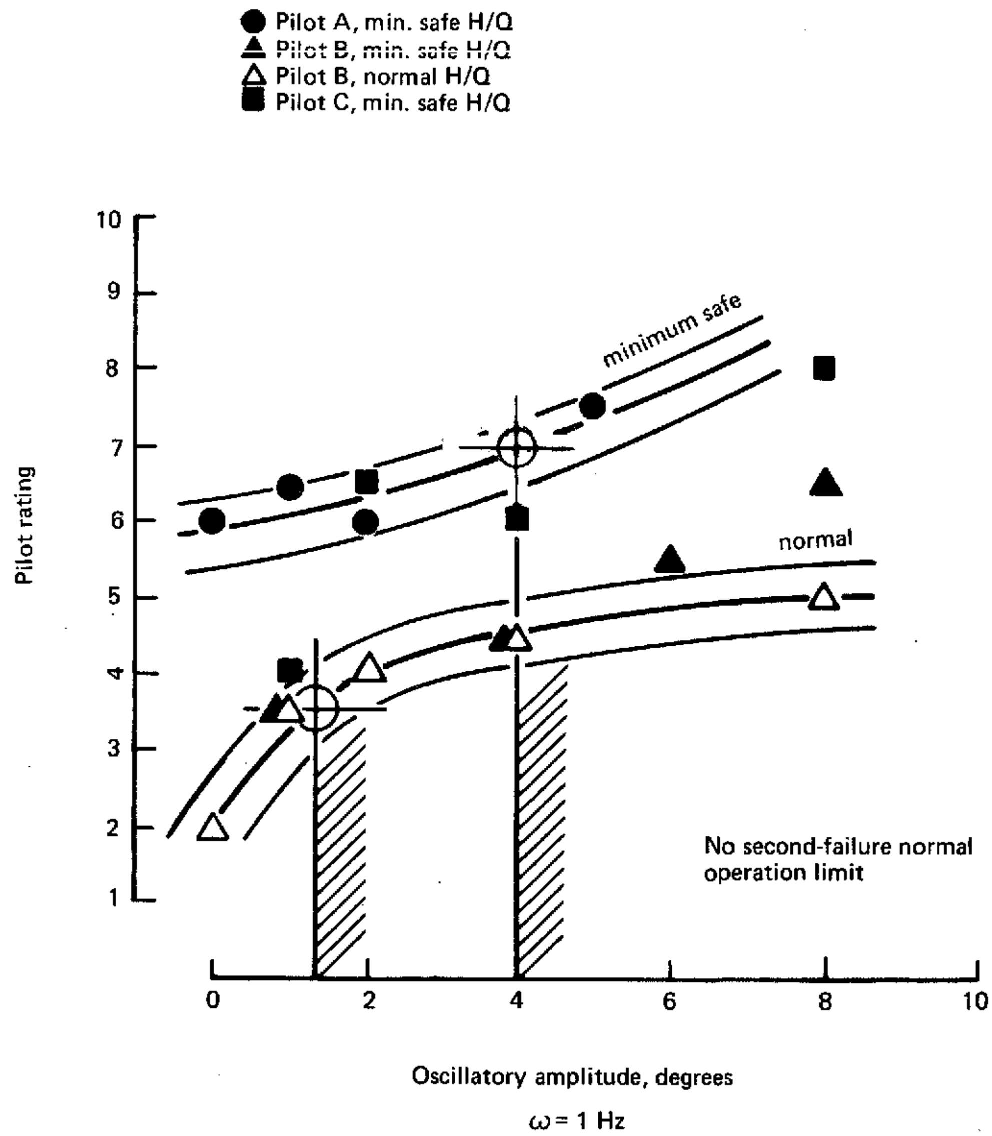


Figure 16.—Landing Approach, Oscillatory Amplitude Sensitivity

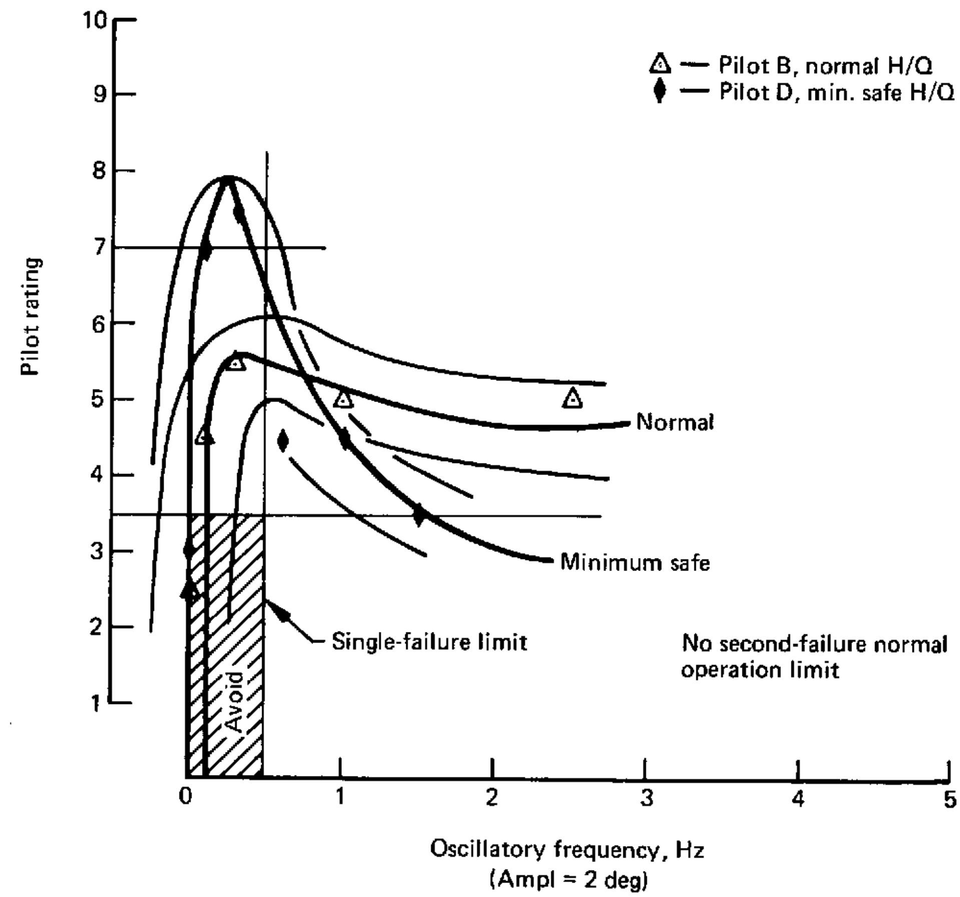


Figure 17.—High Speed Cruise, Oscillatory Frequency Sensitivity

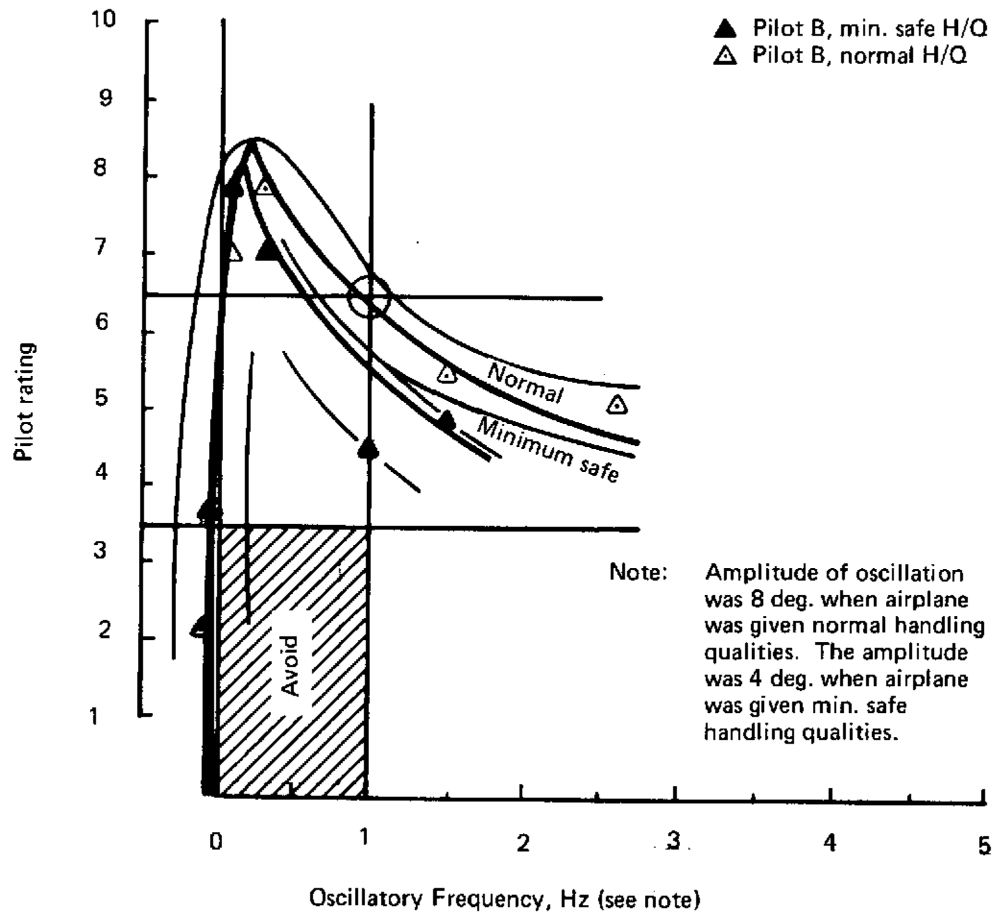


Figure 18.—Landing Approach, Oscillatory Frequency Sensitivity

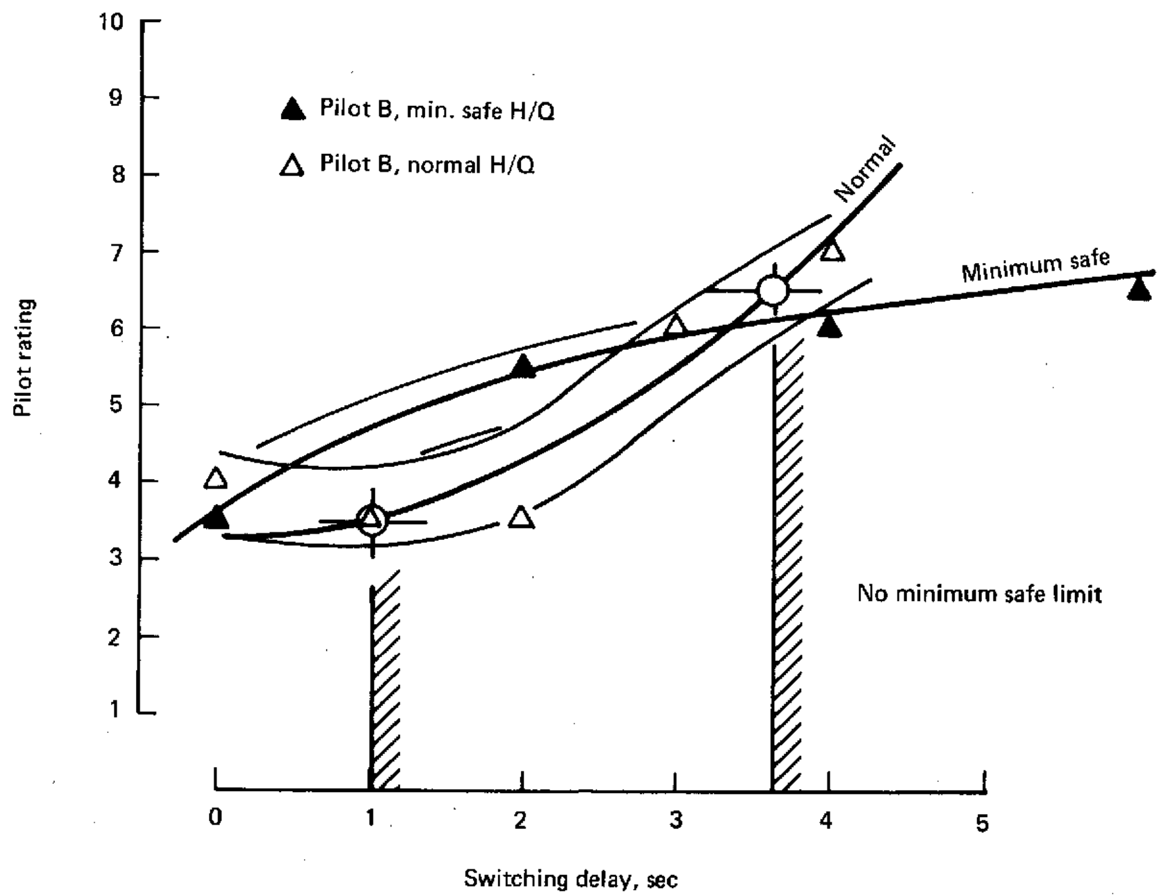


Figure 19.—Landing Approach, Switching Delay Sensitivity

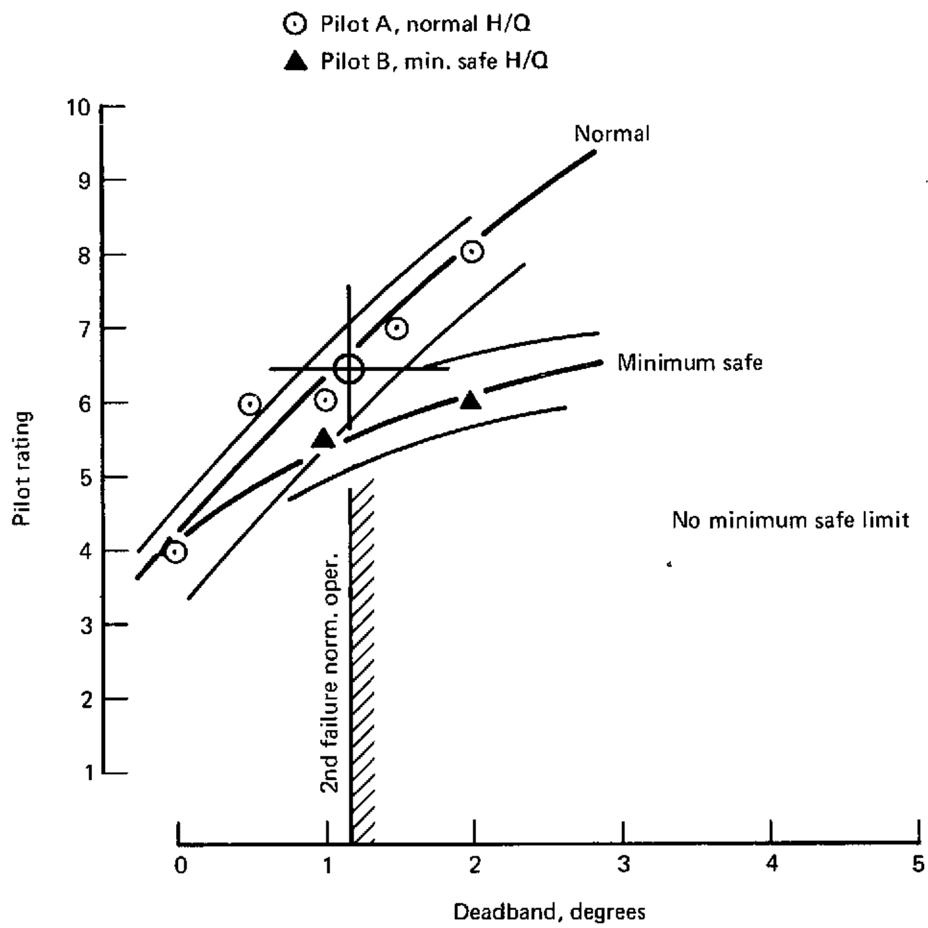


Figure 20.—High Speed Cruise, Deadband Sensitivity

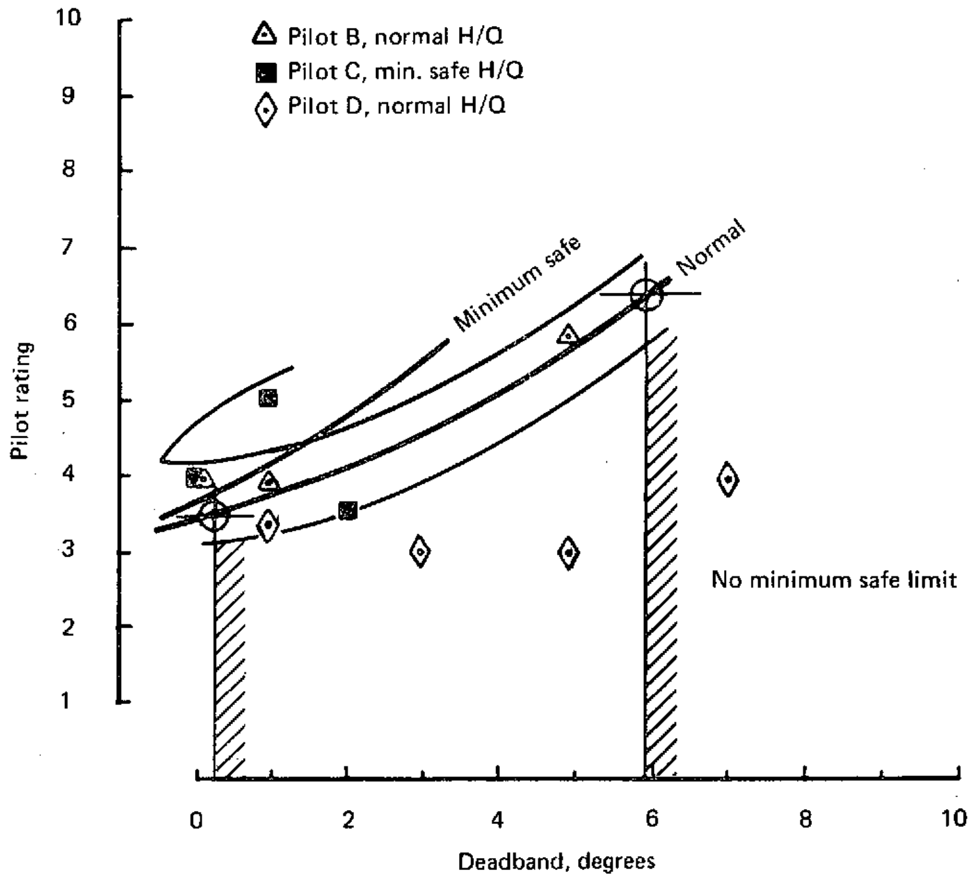


Figure 21.—Landing Approach, Deadband Sensitivity

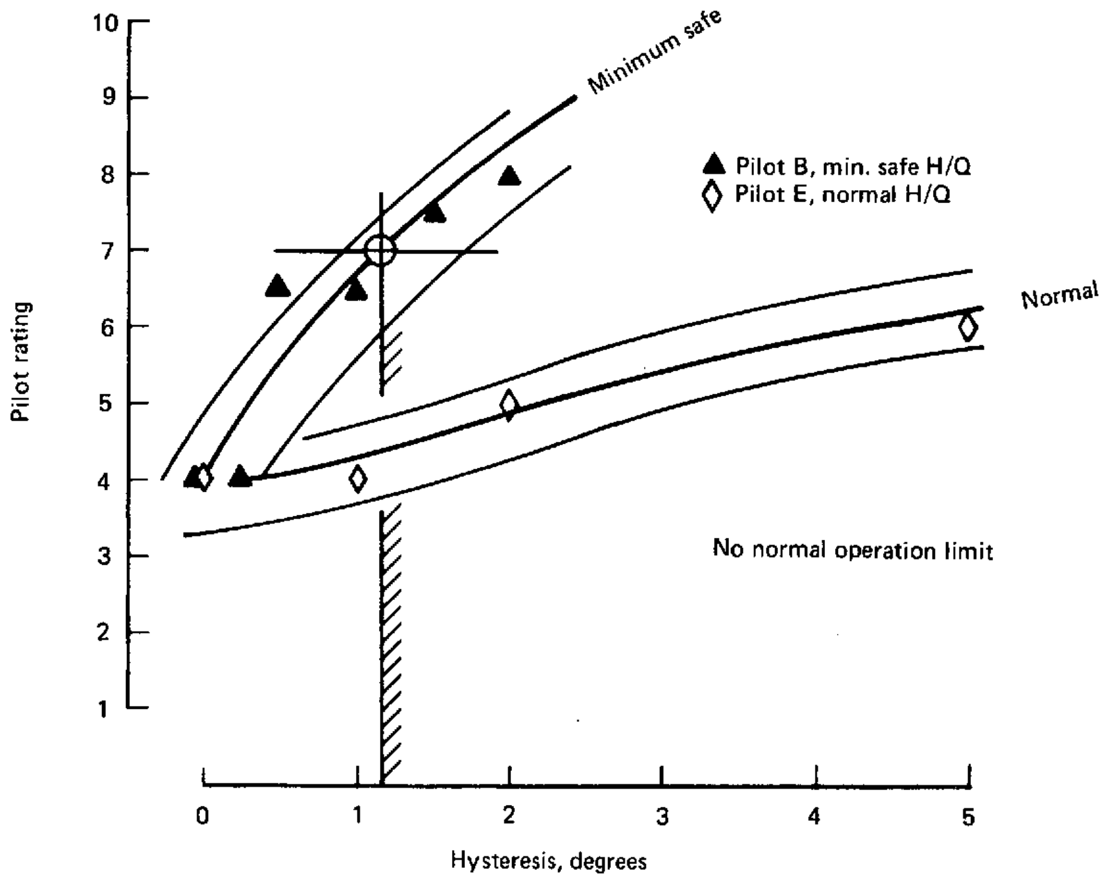


Figure 22.—High-Speed Cruise, Hysteresis Sensitivity

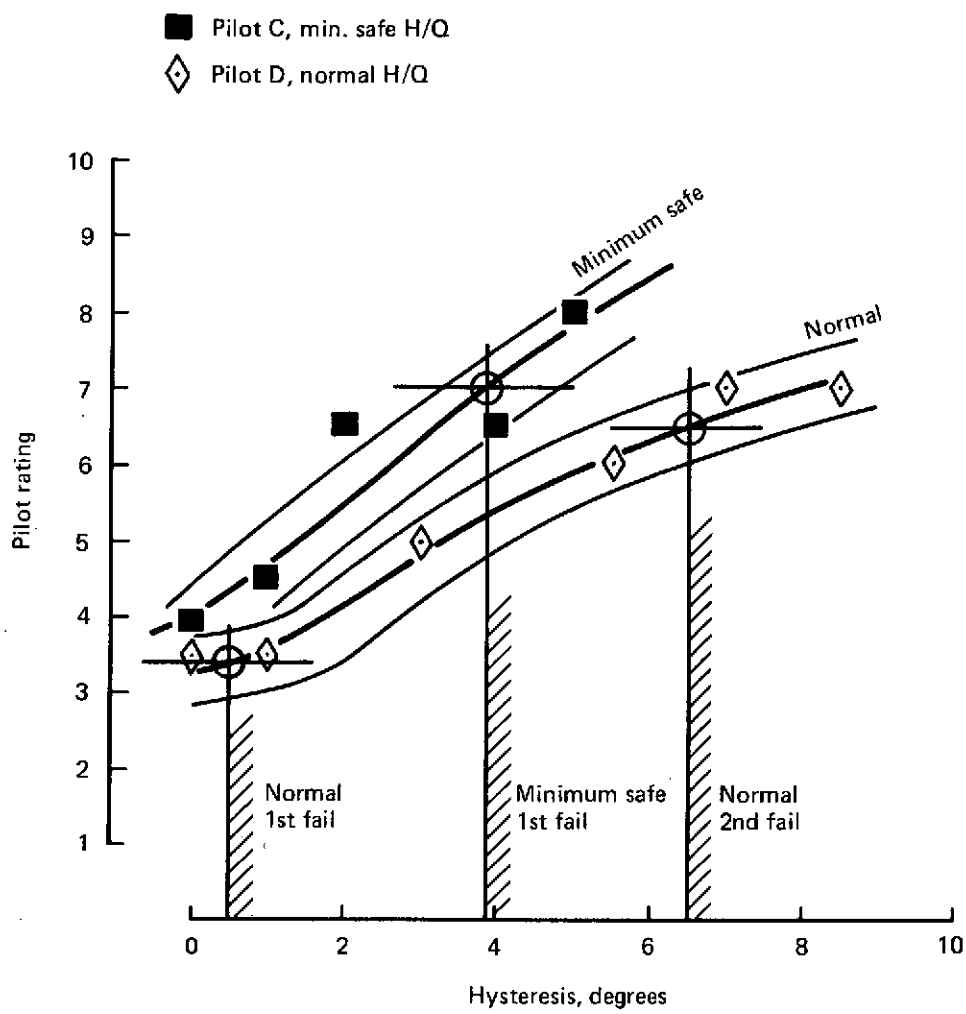


Figure 23.—Landing Approach, Hysteresis Sensitivity

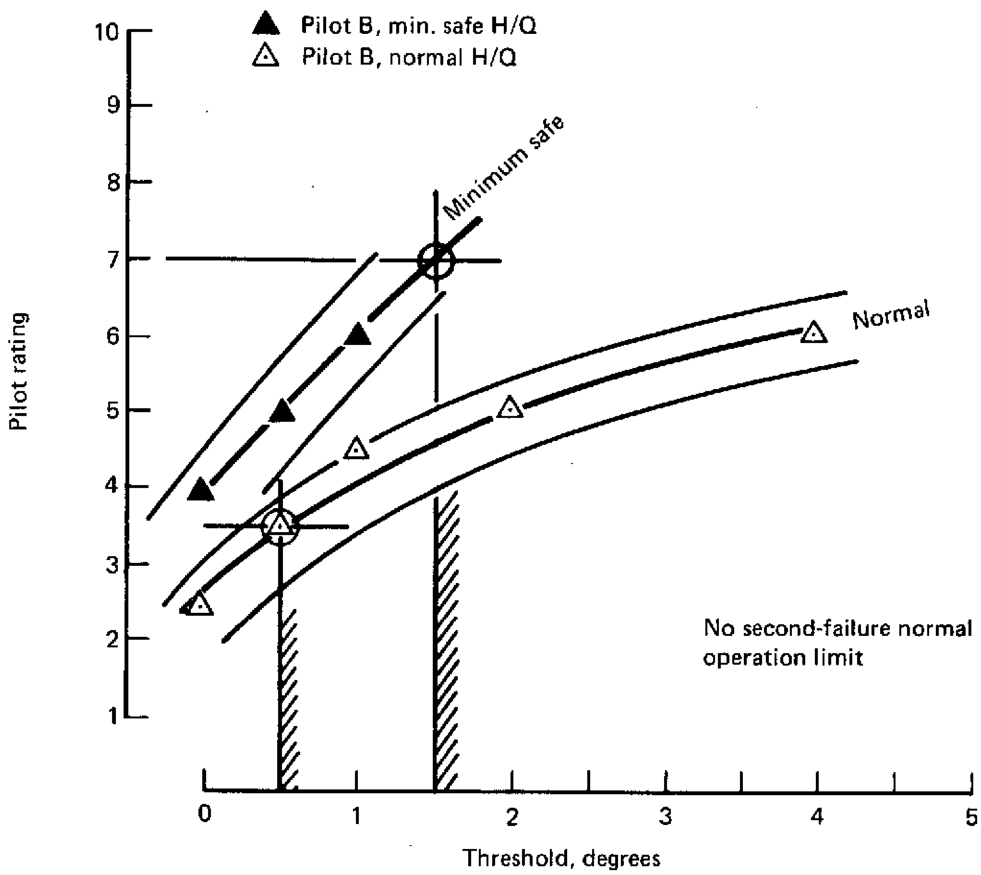


Figure 24.—High-Speed Cruise, Threshold Sensitivity

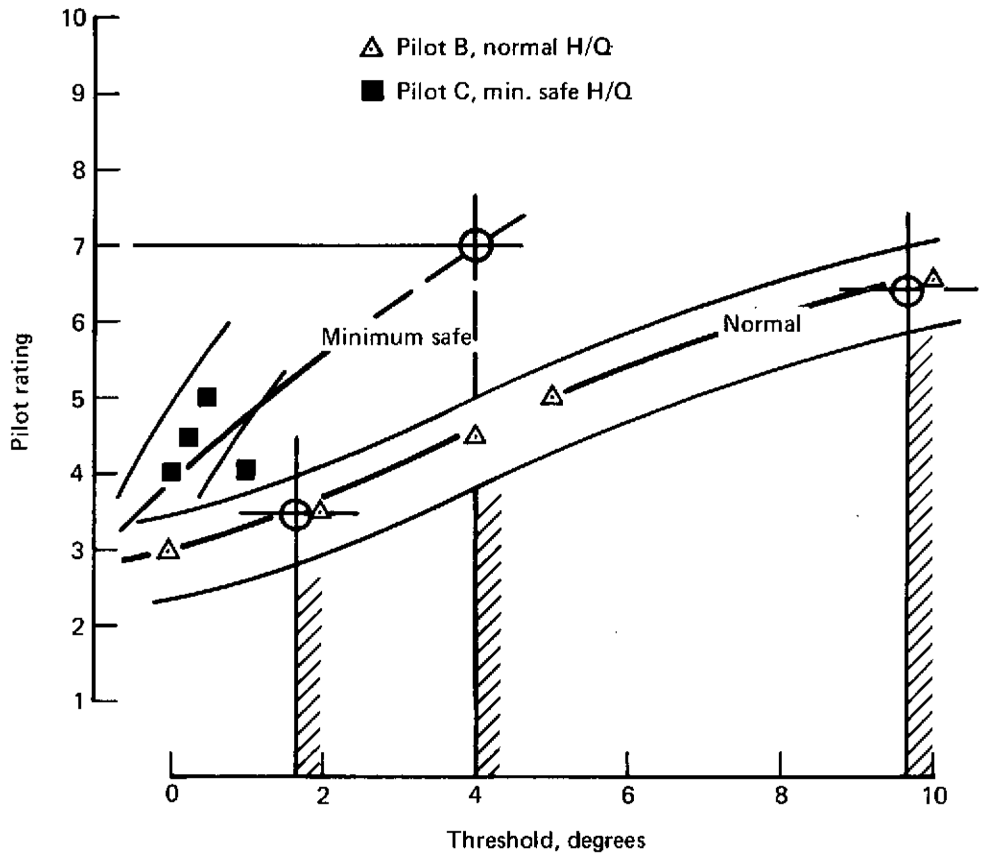


Figure 25.—Landing Approach, Threshold Sensitivity

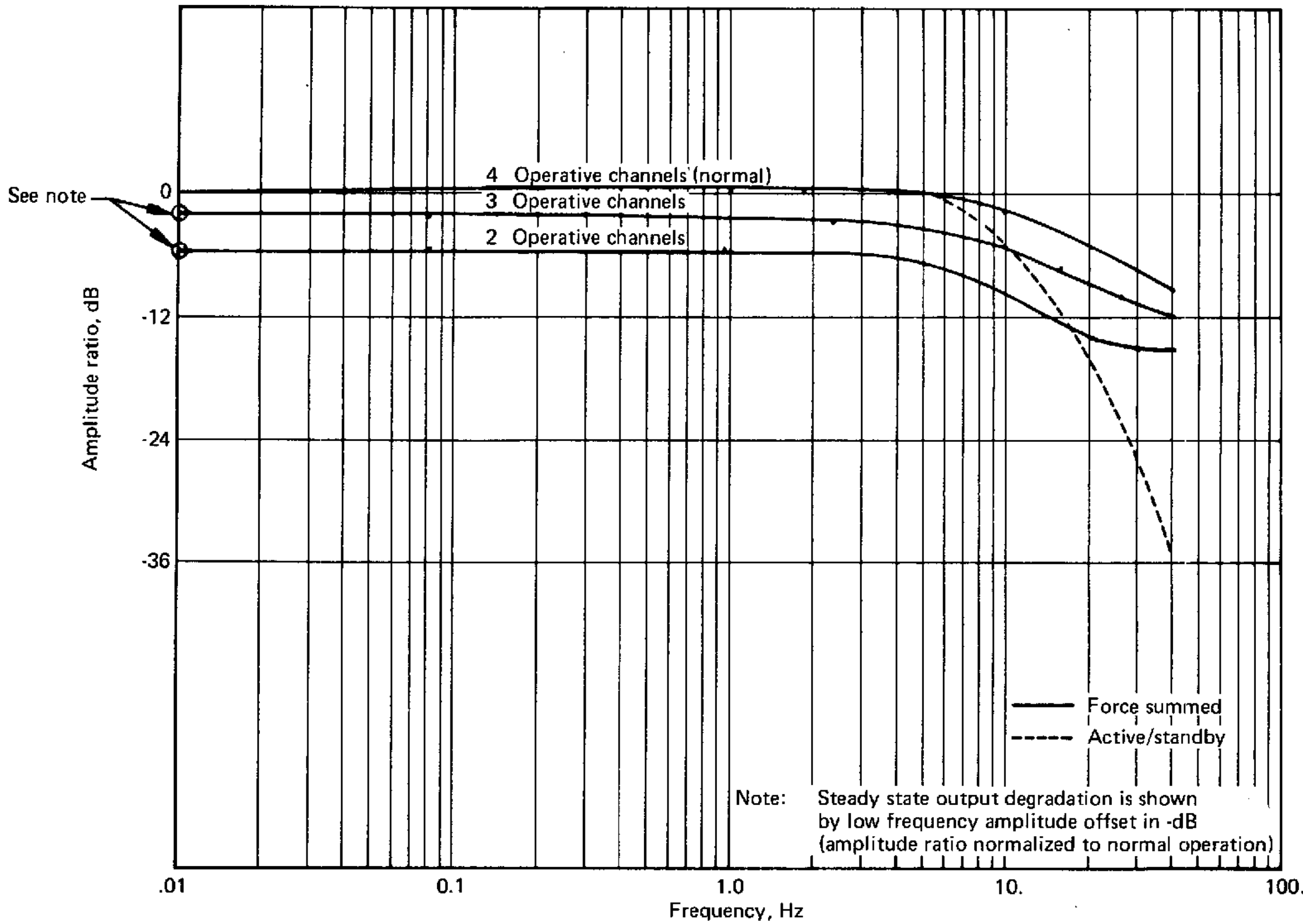


Figure 26.—Frequency Response Performance Degradation Comparison

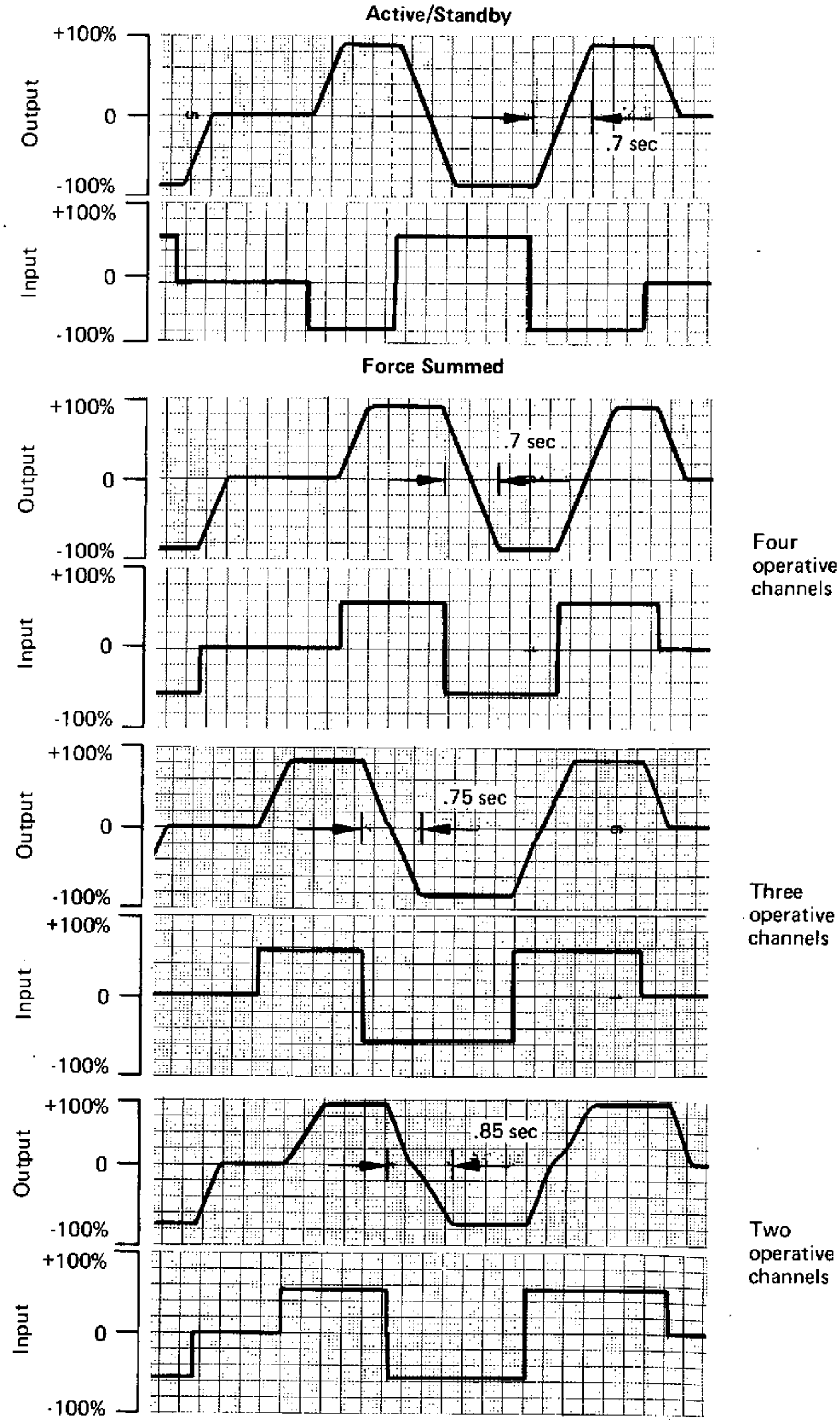


Figure 27.—Transient Response Performance Degradation, Comparison

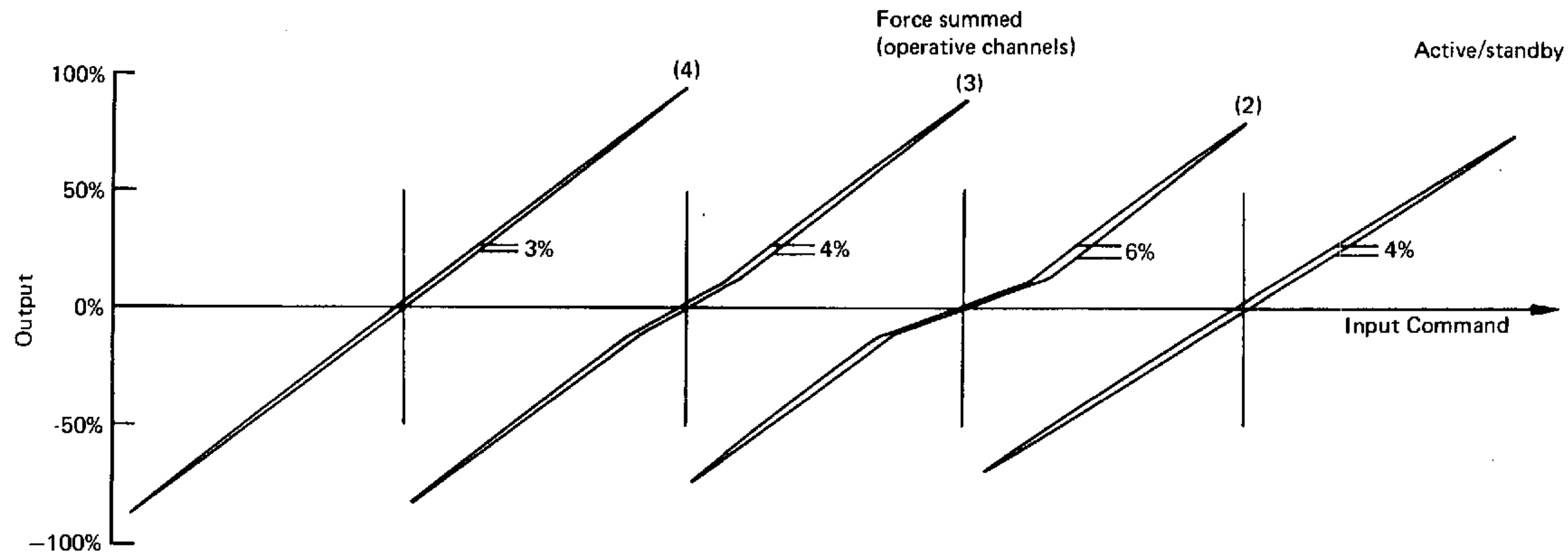
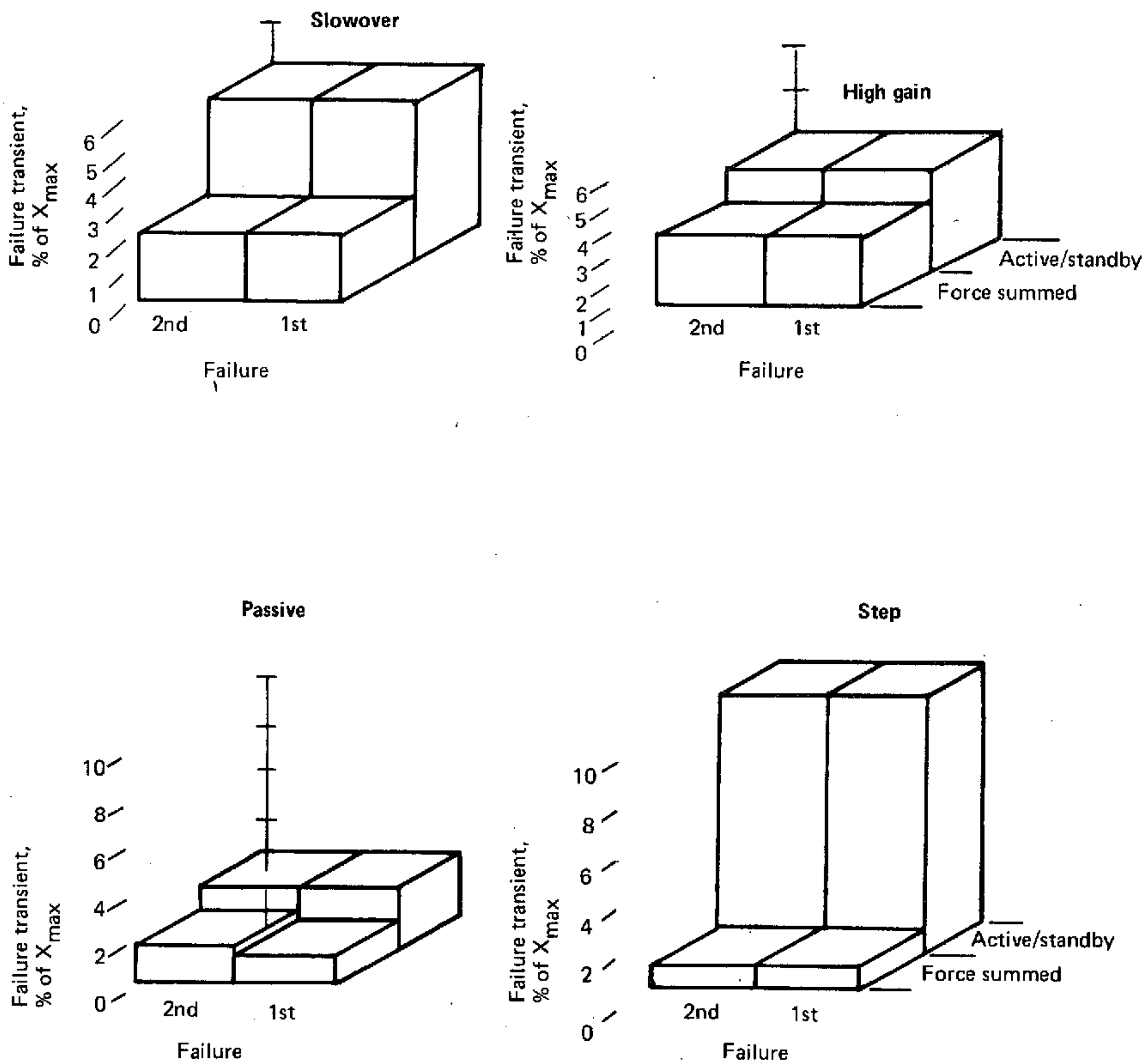
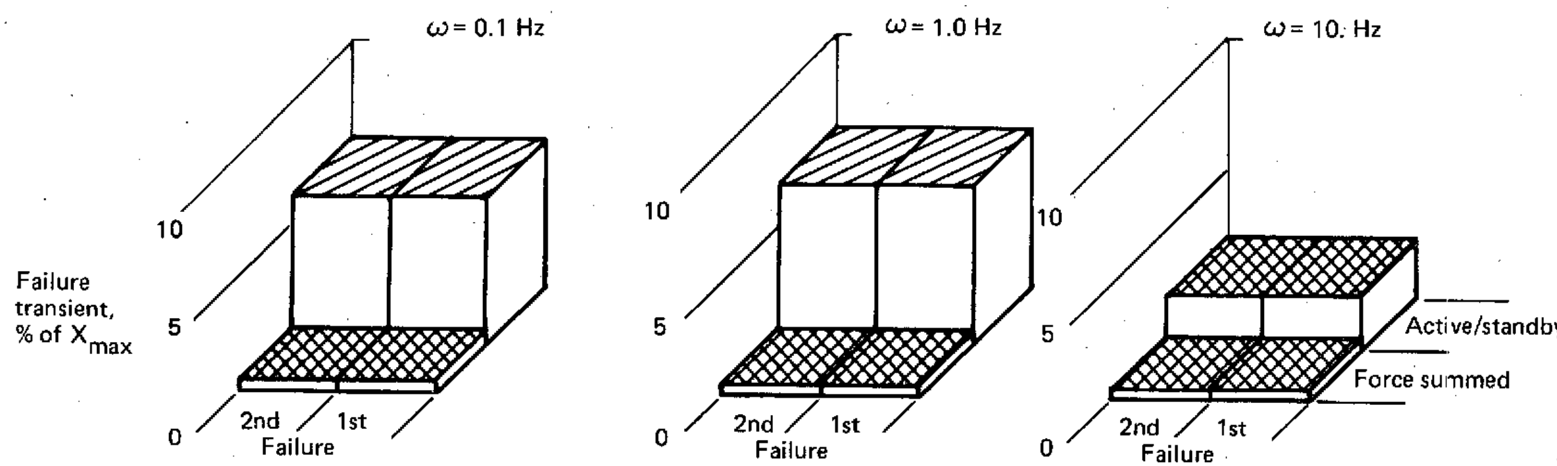


Figure 28.—Resolution Degradation Comparison



Failure type	Failure transient, % of X_{max}			
	Active/standby		Force summed	
	1st failure	2nd failure	1st failure	2nd failure
Slowover	5	5	1.8	1.8
High gain	3	3	2.3	2.3
Passive	3	3	1.0	1.2
Step	10	10	.6	.7

Figure 29.—Failure Transient Slow Over, High Gain, Passive, and Step Comparisons



Failure command		Failure transient, % of X_{max}		
		Active/standby	Force summed	
Ampl % of X_{max}	Freq, Hz		4 operative channels	3 operative channels
10	0.1	7.0	.5	.5
10	1.0	7.0	.5	.5
10	10.	3.0	.3	.3

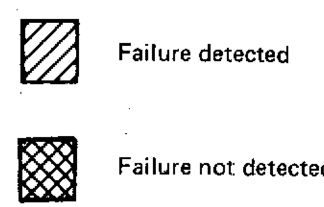


Figure 30.—Oscillatory Failure Transient Comparison

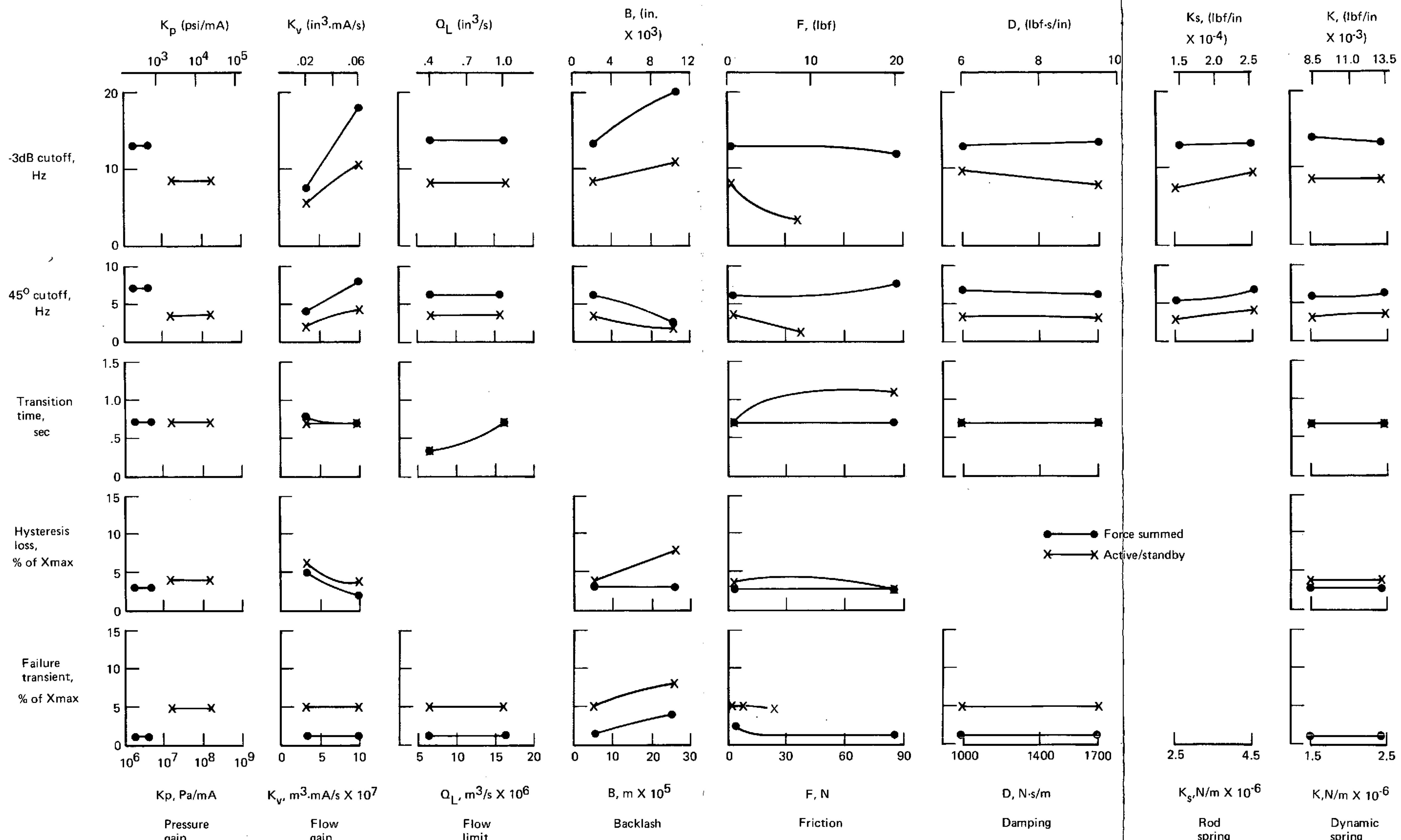


Figure 31.—Design Parameter Sensitivity Comparison

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 1.—Summary of Failure Transient Test Results

Landing Approach

Failure category	Baseline airplane handling qualities level		
	Normal		Min. safe
	1st failure	2nd failure	1st failure
Step, degrees	$\leqslant$1.85	$\leqslant$5.7	$\leqslant$1.85
Oscillatory (ω = 1 Hz) ampl, deg	$\leqslant$1.30	–	$\leqslant$4.0
Oscillatory ω, Hz (1)	$\geqslant$1.0	–	$\geqslant$1.0
Switching delay, sec	$\leqslant$ 1.0	$\leqslant$ 3.65	–

High Speed Cruise (M = 2.7)

Failure category	Baseline airplane handling qualities level		
	Normal		Min. safe
	1st failure	2nd failure	1st failure
Step, deg	$\leqslant$.75	$\leqslant$2.0	$\leqslant$1.15
Oscillatory (ω=1 Hz) ampl, deg	$\leqslant$.25	–	–
Oscillatory (ampl = 2 deg) ω, Hz	$\geqslant$.5	–	$\geqslant$ .5
Switching delay, sec	–	–	–

Note: Failure transient levels represent stabilizer deflection angle.

(1): Min. safe ampl = 4 degrees
normal ampl = 8 degrees

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Table 2.—Summary of Actuator Design Parameter Evaluation Test Results

Landing Approach

Parameter category	Baseline airplane handling qualities level		
	Normal		Min. safe
	1st failure	2nd failure	1st failure
Dead band, deg	⩽.2	⩽5.8	–
Hysteresis, deg	⩽.5	⩽6.5	⩽3.7
Threshold, deg	⩽1.7	⩽9.7	–

High-Speed Cruise (M = 2.7)

Parameter category	Baseline airplane handling qualities level		
	Normal		Min. safe
	1st failure	2nd failure	1st failure
Dead band, deg	–	⩽1.15	–
Hysteresis, deg	–	–	⩽1.15
Threshold, deg	⩽.5	–	–

Note: Parameter magnitudes are given in terms of stabilizer deflection angle.

Table 3.—Actuator Concepts Comparison Summary

Criteria	Active/standby	Force summed
Number of actuator channels	Better	Worse
Normal performance	Worse	Better
Failure performance	Better	Worse
Failure transients	Worse	Better
Safety reliability	Better	Worse
Maintainability	Better	Worse
Vulnerability	Better	Worse
Volume	Better	Worse
Weight	Better	Worse
Cost	Better	Worse

3.0 DESCRIPTION AND RESULTS OF STUDY TASKS

This section, summarized in section 2.0, presents the detailed results of the studies conducted under this contract. Specifically, the study ground rules and approach, the piloted simulation evaluation results, and the concept comparison study results are discussed in the following paragraphs.

3.1 STUDY GROUND RULES

The overall objective of this study was to broaden the technology base for evolving the most suitable and advantageous actuation system concepts for future advanced airplane flight control systems. Two alternative and specific candidate actuation concepts were investigated and evaluated to obtain the basic knowledge and experience of the operational and performance characteristics of the concepts as a basis for determining their applicability and practicality for AST control systems. The study provided a genuine determination of actuator system operating characteristics, handling qualities effects, and various failure modes with flight crew interaction and simulated airplane response. A detailed design definition was produced and comparisons were made of the two systems to evaluate their advantages and disadvantages. A study with the B2707-300 SST simulated on the FSAA at NASA-ARC established allowable limits of critical actuation-system design parameters for use in developing the detailed design definition of the two concepts. This simulation study was conducted in conjunction with the "Development of Handling Qualities Criteria for Large Advanced Supersonic Aircraft" study contract. To determine the applicability and practicality of the candidate actuation concepts for an AST, these concepts were developed and configured in conjunction with a suitable, specific AST requirement. The B2707-300 pitch axis control system as currently mechanized in the NASA-ARC simulation was the basis for formulating the actuation system initial design requirements.

3.2 STUDY APPROACH

The technical approach involved conducting studies in three areas.

A piloted motion simulation using the FSAA at Ames was used to investigate and evaluate the interaction of the pilot and airplane response with performance changes and control transients that occur within the actuation system. This piloted simulation study provided the following data:

1. A control transient evaluation to relate actuator transient variations with pilot rating

2. A design parameter evaluation to relate actuator performance variations with pilot rating

3. A determination of the allowable limits of critical actuation system design parameters

A quantitative evaluation was made of both actuator mechanization concepts to determine their operational and performance characteristics for normal conditions, for failure conditions, and for variations in critical design parameters.

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Actuator math models of the two configurations were developed and simulated on an analog computer. The actuator configurations were developed in as generalized a form as practical to obtain the basic knowledge and experience of the operational performance characteristics of the two concepts. This simulation study provided the following:

1. A detail definition of the configurations and components mechanization

2. An evaluation of failure detection implementation methods

3. An evaluation of normal operational performance

4. An evaluation of performance over a wide range of failures

5. A determination of actuator configuration sensitive parameters

6. A determination of critical actuator system parameters pertinent to the piloted motion simulation study task

In addition to defining the detail mechanizations of the two concepts and determining and comparing their operational and performance characteristics, safety reliability, maintainability, vulnerability, weight, and cost, trade studies were also conducted to aid in establishing a mechanization preference.

3.3 PILOTED SIMULATION STUDY

A piloted motion simulation evaluation was conducted on the FSAA at NASA-Ames. This evaluation corresponded to task 3 of the study contract. This section describes the purpose and background related to the simulation test, presents a summary and conclusions of the evaluation, and discusses the simulation test and test results.

3.3.1 SCOPE AND BACKGROUND

The purpose of the piloted motion simulation test was to define the allowable limits of critical actuation system design parameters for the B2707-300 pitch axis EC servo. This simulator test was conducted with the FSAA at Ames immediately following the second handling qualities simulation session under the base contract, NAS2-7966.

The original plans for this study required analog models of the two study concepts to be interfaced with the digital simulation of the B2707-300 on the FSAA. However, limitations on the analog model frequency content imposed by the sampling rate of the digital simulation and insufficient analog computer hardware, resulted in a reevaluation of the secondary actuator representation to be used in conducting the piloted tests. Thus, a different approach to achieve the same results was needed. The approach selected was to represent the actuator system on the FSAA only; i.e., only digital and no analog representation. The study objectives and purpose remained the same, and would be satisfied. The following considerations were significant in modifying the original plan:

- Analog computer capability permitted only two-channel implementation.

- Analog/FSAA interface limited actuator system natural frequency to less than 2.5 Hz to avoid instabilities.

- Element of risk involved to interface analog simulation to FSAA digital simulation.

- Study objectives could be satisfied (i.e., actuator critical design parameters could be evaluated) with use of FSAA simulation *only*.

- FSAA digital simulation could be increased from 1st to 4th order to improve representation.

- FSAA table look-up routines could be used to simulate transients.

- FSAA could not be programmed to shift from one channel characteristic to another without having to IC the computer.

- No analog simulation required if use FSAA only.

- Flexibility to directly relate the actuator system to airplane performance would be compromised, yet end results would be the same.

- Boeing-based simulation work tasks would be increased to describe and evaluate critical actuator system parameters yet analog implementation task on the FSAA would be eliminated.

The decision not to interface an analog representation of the actuator system with the FSAA is not meant to suggest that interfacing the FSAA with an analog representation (either computer or hardware models) at some other time would not be desirable. At a future time it could be very desirable to evaluate the discrete transient effects and nonlinearities of the actual secondary actuator systems with a piloted motion simulator.

3.3.2 SIMULATION TESTS

The actuation system simulation tests were conducted in conjunction with, and immediately following the second simulation session of the "Handling Qualities Criteria" development testing on the FSAA. The simulator test time was scheduled for two weeks to conduct the actuator system study. The actuator study test was consistent with, and dependent on, the handling qualities work (particularly the FSAA studies) of the basic contract. The airplane configurations and flight conditions were selected on the basis of the handling qualities work.

3.3.2.1 Simulation Configuration

Four airplane test configurations were selected as representative of the B2707-300 aircraft flight control envelope. The four configurations represent a high-speed cruise flight condition and a landing approach flight condition, both within a normal operation boundary and a minimum-safe operation boundary. The longitudinal control characteristics of both flight conditions are depicted on figures 32 and 33.

The longitudinal control system was used for evaluating the control characteristics of the actuation system. Functional diagrams of the control system are shown in figures 9, 10, and 34. A functional diagram of the secondary actuator used in the study is shown in figure 11.

3.3.2.2 Test Results

The testing performed on the FSAA simulator was divided into two categories. The first category evaluated the effects of different control system failure modes on airplane handling qualities. The second category investigated the effects of variations of actuator design parameters on airplane handling qualities. Each test category was evaluated at the four flight conditions described in paragraphs 2.3.1 and 3.3.2.1 which included operation at landing approach and high speed cruise. The airplane configurations were chosen such that the handling qualities bordered on the lower limits of normal and minimum safe operation. At each combination of airplane configuration and flight condition a test sequence was performed with changing actuator characteristics, until clear trends in pilot ratings were established. The test procedure is summarized in table 4.

Figure 35 shows the pilot tasks performed during a typical landing approach test. A similar task outline for the cruise condition is shown in figure 36. Each test was evaluated by the simulator pilot using the Cooper-Harper rating scale. The Cooper-Harper rating scale is shown in figure 37.

The test results of the FSAA evaluation are contained in tables 1 and 2 and figure 13 through 25, and are discussed in paragraph 2.3.4.

3.4 ACTUATION CONCEPT TRADE STUDY

A quantitative evaluation study was made of both actuator mechanization concepts. An analog computer study and an analytical trade study were conducted. The results of these studies follow.

3.4.1 ANALOG SIMULATION EVALUATION

The analog computer simulation study evaluated the operation and performance characteristics of both concepts, and determined the sensitivity of design parameter variations on their operation. The purpose of this study phase was to develop a detailed design definition for each system.

3.4.1.1 Configuration Selection

A computer study was performed using analog models of an active/standby and a force summed secondary servo configuration. These analog models included such nonlinearities as valve flow and pressure limits, friction, and backlash.

Each of the analog models included a representative failure detection network and elements required to eliminate or reduce the effects of nonoscillatory failures.

An oscillatory-failure detection circuit was not included in the analog models. This approach was forced, in that especially the force summed model was taxing the analog computer to its limits in terms of available computing elements. There were an insufficient number of amplifiers to include an oscillatory-failure detection network.

To minimize distortion of the data the characteristics of each model were kept as near alike as possible. For example, the same actuator model (area, friction, flow limit, stroke) was used in both models. The load applied to each system was identical in mass, stiffness, and damping characteristics. An alternative approach was to increase the actuator size in the active/standby system so that the dynamic piston loading would be the same for the two systems. This approach would have required estimation of a new set of actuator parameters, and would have introduced larger uncertainties to the results than the approach taken.

The main disadvantage of the approach taken was that the active/standby system experienced a larger dynamic piston loading which primarily affected the results of the frequency response test data.

3.4.1.1.1 Active/Standby Configuration Selection.—A block diagram of the analog model used to represent the active/standby secondary actuator is shown in figure 38. The elements of one channel are shown in detail, as is the interface with the adjacent channels. Each of the adjacent channels is identical to the channel shown. The major elements in each channel are the servo amplifier (actuator), electrohydraulic servovalve (actuator), piston dynamics, servo amplifier (monitor), and electrohydraulic servovalve (monitor).

The servo amplifiers and electrohydraulic servovalves of each channel and its monitor are identical except as detailed later in this section.

Each of the three channels of the active/standby system are interfaced through the block labeled Load Dynamics. The linkage connecting the secondary actuator to the surface actuators is represented as a finite mass with viscous damping and with a low-force gradient centering spring.

The failure-detection logic shown in figure 38 is mechanized so that channel 1 is normally the active channel. If channel 1 fails, control is transferred to channel 2 provided that channel 2 is operational. If that is not the case, control is transferred to channel 3.

In the configuration selection process, a single-stage and a two-stage electrohydraulic servovalve variant of the active/standby system was tested.

Figure 39 shows the single-stage variant of the system with its monitor network (configuration I). The single-stage valve controls hydraulic flow to the actuator. Differential pressure across the actuator piston is sensed for use in the failure monitoring system. The valve in the channel monitor operates "blocked port." The channel monitor's blocked port pressure is sensed and subtracted from the actuator channel pressure to generate an error signal. The error signal is tested for amplitude and duration. If it exceeds set limits a *failure-detected* signal is transmitted to the logic network to activate a standby channel and deactivate the failed active channel.

The channel monitor pressure typically reached maximum system pressure for all but very small commands. The actuator differential pressure, except for the initial pulse, only reached a fraction of system pressure. Thus, the failure-detection error signal contained very little intelligence about the functional state of the channel, as it always was close to system pressure whenever the piston was in transition.

The two-stage valve variant (configuration II) with its monitor network is shown in figure 40. The two-stage, electrohydraulic servovalve command input to the first stage resulted in a proportional displacement of the second-stage spool.

Mechanical feedback from the second stage to the first stage torque motor provided this proportional control. The displacement of the second stage in turn determined the flow out of the unit.

The first-stage control pressures provided the driving force to position the second-stage spool valve. The algebraic sum of the pressure differential in the actuator channel valve and in the channel monitor valve should be zero if no failure exists. Representative pressure traces in response to a step command is shown in figure 33. Furthermore, since only second-stage spool position is monitored, it is not necessary to implement a flow-control capability in the monitor channel. For this reason, the second stage of the valve in the channel monitor can be simplified. There is no need to include all passages and metering devices, as this valve does not control any flow to a downstream actuator. A plain "dummy" spool, as shown in figure 33, is adequate.

Due to normal variations in system gains, etc., the two signals will never be identical. A combination of an amplitude threshold and a time delay is used to account for these normal variations. It should be noted that these tolerances can be much smaller than those in the previously described single stage system.

A third valve/monitor configuration (configuration III) is shown in figure 41. This one is similar to the single-stage configuration shown in figure 39. The only difference is that this third configuration has a two-stage valve rather than a single-stage valve.

A summary of the tests used in selecting the active/standby, valve/monitor configuration is shown in table 5. These tests all represent failure conditions and are representative of those which the system would be subjected to.

Figures 42 and 43 summarize the test results for configurations I and II. In evaluating these two configurations consideration was given to the magnitude of the output transient ($\Delta X_o/X_{o_{max}}$) due to a failure and to each system's ability to detect and correct for that failure.

Output transients due to system failures in configurations I and II are compared in figure 42. When exposing the active channel to an erroneous ramp command, the output followed the command until an error signal had been present in the failure detection logic long enough for the logic to determine that a failure existed. At this time, control was transferred to a standby channel. Similarly, if this failure occurred in a monitor channel, the logic would detect the failure and transfer control to a standby channel. However, in this case there would be no motion of the output.

A comparison of the performance of the two configurations showed that configuration II experienced less of a transient than configuration I. Pressure and time tolerances can be set much tighter in configuration II than in configuration I, thereby resulting in earlier failure detection.

The *high gain* failure would typically result from the failure of an amplitude feedback loop. When comparing performances for this failure, configuration II proved superior due to the tighter tolerances.

Step failures would result from component failures in the computing elements or drive electronics. When comparing system performances to these failures, configuration II showed smaller transients for large steps but gradually approached the same performance as configuration I as the step amplitudes decreased. During these tests it was found that there was a cutoff point in step amplitudes below which the system did not detect a failure due to the respective monitor network error signal thresholds.

System responses to oscillatory failures are compared in figure 43. Oscillatory failures are typically generated by the computing elements or drive electronics. The failure detection network required to detect oscillatory failures was not modeled on the analog computer. The criterion whether or not the system would be able to detect an oscillatory failure was the error signal magnitude above the detection threshold. Both configurations displayed the same peak amplitudes. However, configuration II had a somewhat greater ability to detect failures at higher frequencies.

Comparing the results of the testing of these two configurations, configuration II perfoms better under failure conditions than does configuration I.

No quantitative testing was conducted on configuration III due to the similarity to configuration I. Performance under failure conditions would be similar to configuration I, and inferior to configuration II. This conclusion was verified by spot checks.

As a result of the testing, configuration II was selected as the candidate active/standby secondary servo to be compared with the force summed servo.

3.4.1.1.2 Force Summed Configuration Selection.—A block diagram of the analog model used to represent the force summed secondary actuator is shown in Figure 44. One channel with its equalization circuit is shown in detail. Three additional channels are tied to the common output to make up the redundant control unit. Each of the redundant channels are identical to the one channel shown. The major elements of each channel are the servo amplifier, electrohydraulic servovalve, piston dynamics, equalization circuit, failure detection logic, and centering detent.

The four channels are connected in the block labeled load dynamics. This block also simulates a representative load consisting of a finite mass with viscous damping and low gradient centering spring. In normal operation, all four pistons move in unison, commanded by identical command signals. When a failure is detected the failed channel is depressurized and a centering detent is engaged. This function is accomplished by the channel disengage relays and associated networks.

The equalization network shown in the diagram (fig. 44) increases the system's tolerance to differences in the four command signals. It is made up of two parallel paths, one integral and one proportional. The proportional feedback path in effect reduces the actuator force gain, thereby reducing the level of force fight within the system. It is intended to handle short term differences in signal levels due to minor gain variations, etc. The integral path is intended to reduce the effects of long term differences between the individual command signals. This is done by integrating up a "trim signal" that will cancel any steady state bias in a command signal.

Channel failures cause either the pressure feedback signal in the proportional feedback path or the trim signal in the integral path to exceed a preselected failure threshold level for a preselected time interval.

A force summed secondary actuator can be designed with a single-stage or a two-stage electrohydraulic servovalve (fig. 45.) Assuming that the maximum flow requirement is the same regardless of valve type used, the differences between a single-stage and a two-stage valve is the pressure gain. To limit the force fight in the system, the proportional pressure feedback path is used to reduce the force gain to acceptable levels. With this pressure feedback, valve pressure gain has little meaning since the system pressure gain is forced to a particular value by the pressure feedback loop. However, if pressure feedback can be eliminated by using single stage valves, and if this does not severely impair performance, a reduction in cost and complexity would be possible.

Table 6 summarizes the tests used in the selection of the valve configuration. Six different valve pressure gain values were selected and a series of performance tests were conducted with each valve configuration. Two of the valve configurations were also selected for performance testing under failure conditions, as noted in table 6.

Figure 46 summarizes the results of the frequency response testing. The observed data shows that valve pressure gain variations had little effect on frequency response. There was some scatter in data, but no apparent trends. For this reason, envelopes were drawn to bound the regions within which the data points were located.

A summary of transient response testing and resolution testing is shown in figure 47. Valve pressure gain affected transient times only when it reached very low values such that the initial acceleration was significantly reduced.

Actuator resolution capability was not affected by variations in valve pressure gain. This result was expected as this type of actuator has great acceleration capability and low friction.

Figure 48 summarizes the test results of the frequency response testing of the force summed secondary actuator under failure conditions. Two valve configurations were used in this test sequence as noted in table 6. The frequency response characteristics were determined for each of the two configurations with all channels operational, with one channel failed and with two channels failed.

The transient response data under failure conditions are summarized in figure 49. Variations in pressure gain had only minor effect on actuator performance. Channel failures, on the other hand, resulted in considerable performance degradation. This was due in part to the fact that the force output of the actuator was reduced by the depressurization of a failed channel, and in part to the engagement of centering detent in each failed channel. The force capability of this detent amounts to approximately 50% of one channel's force capability. Also, the depressurized channel acts as a viscous damper and generates a considerable retarding force as velocity increases.

The resolution testing is summarized in figure 50. Again, variations in pressure gain had little effect on system performance, however hannel failures resulted in a considerable performance degradation. Another observation made during the resolution testing was that with all channels operating no deadband was noticeable. However, as channels were failed a considerable deadband did develop as shown in figure 50. The magnitude of the deadband was considerably greater than the magnitude of the hysteresis.

Figure 51 contains a plot of required pressure feedback versus valve pressure gain to satisfy the criteria for interchannel force fight. This plot indicates that the pressure feedback loop could be removed if the valve pressure gain is sufficiently low.

The trend in all valve configuration selection tests was that valve pressure gain had little effect on the performance of a force summed secondary actuator with an external pressure feedback loop to satisfy a force fight requirement. Only when the valve pressure gain drops below values typical for a single-stage servovalve does it cause any performance reduction. Therefore, a single-stage servovalve configuration was selected for the force summed secondary actuator. This configuration would be used in the performance testing to be compared with the active/standby concept.

In order to make the force summed model directly comparable to the active/standby it was also decided to remove the integral feedback path. Thus, the final configuration has neither the proportional nor integral pressure feedback paths. It uses the piston differential pressure signal for failure monitoring. This signal is evaluated for amplitude and duration to determine if a failure condition is present.

3.4.1.2 Normal Operation Performance Evaluation

The active/standby and force summed systems, as described in paragraph 3.4.1.1, with nominal valued parameters, shown in table 7, and without failures were considered to be the normal systems. Normal performance characteristics were determined for both actuator configurations on an analog computer. The normal performance testing provided baseline frequency response, transient response, and resolution data for overall system evaluation. Table 8 presents a summary of the test procedures used for the testing.

3.4.1.2.1 Active/Standby Test Results.—The active/standby frequency response characteristics under normal conditions is shown on the Bode plot of figure 52. The system amplitude response showed slight peaking between 0.4 Hz and 5 Hz. The amplitude response started to roll off at 5 Hz, and at 8.5 Hz and -3 dB, and at 40 Hz was -35 dB. The system phase lag data showed a slight phase lag at 0.1 Hz, and 45° phase lag at 3.5 Hz, and a 90° phase lag at 7 Hz.

The system transient test showed a transition time of 0.7 second. The transition time corresponds to an output rate of 0.033 m/sec (1.3 in./sec) which is equivalent to the control valve saturated flow rate.

Figure 53 shows an X-Y plot of the normal system steady state output position versus input command. The largest hysteresis loss, 4% (f.s.), occurred near the null position. The hysteresis losses are attributed to friction, backlash, and system tolerances.

3.4.1.2.2 Force Summed Test Results.—The force summed frequency response data characteristic under normal conditions is shown on the Bode plot of figure 54. The system amplitude response showed a slight peaking between 0.4 Hz and 5 Hz. The amplitude response started to roll off at 5 Hz and at 13.5 Hz was -3 dB, and at 40 Hz was -9 dB. The phase lag was slight at 0.1 Hz, 45° at 6.0 Hz, and 90° at 18 Hz

The system transient response test showed a transition time of 0.7 sec. This transition time corresponds to an output rate of 0.033 m/sec (1.3 in /sec), which is equivalent to the control valve saturated flow rate.

Figure 55 shows an X-Y plot of the normal system steady state output position versus input command. The largest hysteresis loss, 3% (f.s.) occurs near the null position. The hysteresis losses are attributed to friction, backlash, and system tolerances.

3.4.1.3 Parameter Sensitivity Evaluation

The active/standby and the force summed systems, as described in paragraph 3.4.1.1 were evaluated as to their sensitivity to certain design parameters.

Both actuator configurations were modeled on an analog computer where specific tests were conducted to determine the effects of the parameter variations. Frequency response, transient response, and resolution response tests were conducted. Table 8 presents a summary of the test procedures used for the testing.

3.4.1.3.1 Active/Standby Test Results.—Table 9 is a list of the study parameters and their variations. The test data showed the active/standby configuration to be sensitive to certain parameters. The following discusses the active/standby system sensitivity to the study parameters. A summary of the most significant data is shown in table 10.

Pressure Gain: The pressure gain parameter, K_p, was varied from 13.8×10^6 Pa/mA to 13.8×10^7 Pa/mA (2000 psi/mA to 20000 psi/mA). The nominal K_p was 6.9×10^7 Pa/mA (10000 psi/mA). The system performance (frequency response, transient response, and resolution) was not noticeably affected by these K_p variations.

Flow Gain: The flow gain, K_V, was varied from 3.3×10^{-7} $m^3 \cdot mA/s$ to 9.9×10^{-7} $m^3 \cdot mA/s$ (0.02 $in^3 \cdot mA/s$ to 0.06 $in^3 \cdot mA/s$). The nominal K_V was 6.5×10^{-7} $m^3 \cdot mA/s$ (0.04 $in^3 \cdot mA/s$).

The active/standby system dynamic response showed K_V dependence for small sinusoidal command signals (±5% F.S.), (fig. 56). The -3 dB cutoff frequency varied from 5 Hz to 10 Hz. The frequency response (for small command signals) is directly related to a change in K_V since a small sinusoidal command signal does not flow-saturate the control valve. For larger command signals, where the control valve would become flow saturated, there would be no K_V dependence.

The active/standby system transient response was not sensitive to K_V variations within the tested limits.

Active/standby resolution data showed that the system output hysteresis varied from 6% (f.s.) for a K_V of 3.3×10^{-7} $m^3 \cdot mA/s$ (0.02 $in^3 \cdot mA/s$) to 4% (f.s.) to a K_V of 9.9×10^{-7} $m^3 \cdot mA/s$ (0.06 $in^3 \cdot mA/s$) (fig. 57).

Flow Limit: The control valve flow limit, Q_L was varied from the nominal flow limit of 6.5×10^{-6} m^3/s to 1.6×10^{-5} m^3/s (0.395 in^3/s to 0.955 in^3/s). The actuator transient response characteristics showed a decrease in response time for an increased Q_L (fig. 58). The transition time decreased linearly from 0.7 sec* to 0.3 sec for an equivalent proportionate increase in Q_L. No other active/standby performance characteristics were noticeably affected.

Backlash: The system backlash, B, was varied from the normal backlash of 5.1×10^{-5} m to 2.54×10^{-4} m (0.002 in. to 0.010 in.). The system frequency response (due to ± 5% f.s. sinusoidal command) data and resolution data showed B dependence. Transient response tests were not conducted for B variations, because they do not effect the output rate (i.e., transition time).

The -3dB cutoff frequency varied from 8.5 Hz to 10.5 Hz for the extreme B values. The 45 phase lag frequency was 3.5 Hz and 1.7 Hz for the same B variation (fig. 59). The amplitude response data increased in amplitude output as B increased. An explanation is that when the actuator reached the commanded position, the system inertia coupled with an increased B allowed the actuator output to overshoot the commanded position. The increased phase lag as B increased was due to the lost motion. That is, position output would neither start nor stop moving in the commanded direction until the actuator output traveled the backlash distance.

Resolution data showed hysteresis losses of 4% (f.s.) and 8% (f.s.) for B equal to 5.1×10^{-5} m and 2.54×10^{-4} m (0.002 in. and 0.010 in.), respectively (fig. 60). This is due to the lost motion in the output.

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*The transition time of 0.7 sec is the time for the system to respond to a 90% command, see table 10.

Friction: The system friction, F, was varied from 1.8 N to 89 N (0.4 lbf to 20 lbf) with a nominal F of 1.8 N (0.4 lbf).

System frequency response data showed that the -3 dB cutoff frequency varied from 8.5 Hz to 3.5 Hz for F equal to 1.8 N and 35.6 N (0.4 lbf and 8 lbf), respectively. The 45° phase lag frequency varied from 3.5 Hz to 1.5 Hz for those same F values (fig. 61).

Transient response data showed F dependence. The system transition time varied from 0.7 sec* to 1.1 sec for F equal to 1.8 N and 89 N, respectively (fig. 62).

Resolution data showed that the system hysteresis varied from 4% to 12% (f.s.) for the nominal configuration and F of 89 N (20 lbf), respectively (fig. 63).

For any friction type output load, a certain equivalent input command is required to generate sufficient actuator output force to overcome the friction restraint and cause the output to respond (i.e., move). This command level is therefore effectively lost and reflected as degraded frequency response, degraded transient response, and increased hysteresis loss.

Damping: The damping parameter, D, was varied from 1059 N • s/m to 1750 N • s/m (6 lbf • s/in. to 10 lbf • s/in.). The nominal D was 1400 N s/m (8 lbf • s/in.). The system transient response data were not noticeably affected by these D changes. The frequency response data showed slight D dependence (fig. 64). Resolution tests were not conducted since D is a velocity dependent parameter and resolution tests are conducted in a manner to minimize such velocity effects.

Actuator Rod Stiffness: The actuator rod stiffness, K_s was varied from 2.6 x 10^6 N/m to 4.4 x 10^6 N/m (15 000 lbf/in. to 25 000 lbf/in.). Variations of K_s only slightly affected the system frequency response (fig. 65). Transient response and resolution tests were not conducted for variations of the rod stiffness.

Actuator Dynamic Stiffness: The actuator dynamic stiffness, K, was varied from 1.5 x 10^6 N/m to 2.4 x 10^6 N/m (8500 lbf/in. to 13 500 lbf/in.), with a nominal K of 1.9 x 10^6 N/m (11 000 lbf/in.). None of the system performance characteristics (frequency response, transient response, and resolution) were sensitive to changes of K.

3.4.1.3.2 Force Summed Test Results.—Table 11 is a list of the study parameters and the parameter values utilized to determine the force summed performance characteristics. A summary of the most significant data is shown in table 12. Test data showed the force summed system to be sensitive to certain parameter variations. These are discussed below.

Flow Gain: The flow gain, K_v, was varied from 3.3 x 10^{-7} m^3 • mA/s to 9.9 x 10^{-7} m^3 • s/mA (0.02 in^3 • mA/s to 0.06 in^3 • mA/s). The nominal K_v was 6.5 x 10^{-7} m^3 • s/mA (0.04 in^3 • mA/s. Changes in K_v affected both frequency response and resolution data, but did not noticeably affect the transient response data.

*Transition time of 0.7 sec is the time for the system to respond to a 90% command, see table 10.

The -3 dB cutoff frequency varied from 7.5 Hz to 18 Hz (fig. 66) for the extreme K_V values. The 45 cutoff frequency was 4.0 Hz and 8 Hz for the same extreme K_V values. The frequency response for small command signals of this system is directly related to a change in K_V, since a ±5% sinusoidal command signal does not flow-saturate the control valve. Whenever the control valve is operating in a flow saturated region (i.e., large commands), there will be no K_V dependence.

Resolution data showed that the system output hysteresis, figure 67, varied from 5% (f.s.) to 2% (f.s.) for K_V equal to 3.3×10^{-7} $m^3 \cdot$ mA/s and 9.9×10^{-7} $m^3 \cdot$ mA/s (0.02 $in^3 \cdot$ mA/s and 0.06 $in^3 \cdot$ mA/s, respectively.

Flow Limit: The flow limit, Q_L, was varied from the nominal Q_L of 0.65×10^{-5} m^3/s to 1.6×10^{-5} m^3/s (0.395 in^3/s to 0.955 in^3/s). Frequency response data showed no Q_L sensitivity, because the control valve was not flow saturated for any of the flow limit testing. The transient response characteristics showed that the actuator transition time* varied from 0.7 sec to 0.3 sec for Q_L equal to 0.65×10^{-5} m^3/s and 1.6×10^{-5} m^3/s (0.395 in^3/s and 0.955 in^3/s), respectively.

Backlash: The system backlash, B, was varied from the nominal value 5.1×10^{-5} m to 2.54×10^{-4} m (0.002 in. to 0.010 in.).

The frequency response data showed B dependence (fig. 68). The -3 dB cutoff frequency varied from 13.5 Hz to 20 Hz for the extreme B values. The 45° cutoff frequency was 6.0 Hz and 3.0 Hz for those same B values. The increased amplitude response may be due to the system inertia coupled with backlash allowing the actuator to overshoot and cause an apparent improvement in the amplitude response data. The phase lag degradation with respect to increased B is due to lost motion.

The force summed system resolution data showed no B dependence (fig. 69). The reason is that the four channels are force fighting one another in such a way to preload the system, and effectively eliminate any backlash effects. Thus, the changes that are made in B, would not be apparent whenever the system was operated in a nearly steady-state mode (i.e., during the resolution testing).

Friction: The force summed system friction, F, was varied from 1.8 N to 89 N (0.4 lbf to 20 lbf), with a nominal F of 1.8 N (0.4 lbf). The system performance (frequency response, transient response, and resolution) showed no F dependency for friction values less than 35.6 N (8 lbf). Frequency response data showed that some performance degradation occurred for a friction value of 89 N (20 lbf) (fig. 70).

Damping: The damping parameter, D, was varied from 1050 N · s/m to 1750 N · s/m (6 lbf · s/in. to 10 lbf · s/in.), and the nominal D was 1400 N · s/m (8 lbf · s/in.). System transient response data was only slightly affected by D variations. This slightly-observed effect was assumed to be within experimental data tolerances.

*The transition time of 0.7 sec is the time for the system to respond to a 90% command, see table 12.

Actuator Rod Stiffness: The actuator rod spring, K_s, was varied from 2.6×10^6 N/m to 4.4×10^6 N/m (15 000 lbf/in. to 25 000 lbf/in.), with a nominal K_s equal to 3.5×10^6 N/m (20 000 lbf/in.). Variations of K_s did not noticeably affect the system frequency response. The rod spring was not varied for either the transient response or the resolution test procedures.

Actuator Dynamic Stiffness: The actuator dynamic stiffness, K, was varied from 1.5×10^6 N/m to 2.4×10^6 N/m (8500 lbf/in. to 13 500 lbf/in.), with a nominal K of 1.9×10^6 N/m (11 000 lbf/in.). None of the system performance characteristics (frequency response, transient response, and resolution) were sensitive to the tested K variations.

Voltage Offset: The voltage offset, Δv, was varied from 0 (zero) % to ±2.5% of the full scale command, with a nominal Δv of 0%. The system frequency response, transient response, and resolution tests showed no effect due to Δv under normal conditions.

3.4.1.4 Failure Effects Evaluation

Failure tests were conducted on the active/standby and force summed actuator configurations to show how the respective output transients vary due to different failure types (i.e., slowover, step, oscillatory, passive, and high gain). For all failure conditions, except for the slowover failure, the system parameters were kept at their nominal value. The slowover failure testing was conducted with parameter variations to show this effect on output performance. The slowover testing was conducted by varying critical design parameters separately and independently of the others and then introducing a slowover failure. Typical actuator failure response characteristics are shown on figures 71 through 74.

3.4.1.4.1 Active/Standby Test Results

3.4.1.4.1 Active/Standby Test Results: A block diagram of the active/standby system is shown in figure 7 to facilitate the discussion of failure types and failure test procedures peculiar to the active/standby concept. The active/standby system as tested includes a failure monitoring concept as described in paragraph 3.4.1.1. Although certain oscillatory failure conditions were detectable as slowovers, no failure logic was implemented specifically to detect oscillatory failures. The failure monitor system is not an optimized configuration. However, the configuration is suitable for comparing the relative characteristics of the two actuator concepts being studied.

Failure Definition and Test Procedure: The following discussion defines the types of failures and the test procedure used in determining the effects of, and sensitivity to certain failure conditions.

A *slowover* failure is an erroneous signal in the form of a ramp input command to one or more of the six active/standby channels. Tests were conducted by introducing a ramp command signal into channel A_c (fig. 7). All other channels had no input commands. In addition to determining the nominal system transient behavior due to a slowover failure, certain specific design parameters were independently varied to determine the failure sensitivity to parameter variations.

An *oscillatory* failure is an erroneous signal in the form of a periodic input command (e.g., sinusoidal) into one or more of the six active/standby channels. To determine the effect of oscillatory failures, a sinusoidal command was introduced into channel A_C (fig. 7). All other channels had no input commands.

A *step* failure is an erroneous signal in the form of a step input command to one or more of the six active/standby channels. Tests were conducted by introducing a step command signal into channel A_C (fig. 7). All other channels had no input commands.

A *high gain* failure is a failure condition caused by an open feedback in one of the six active/standby channels. Consequently, no output position information is being fed back to compare (algebraically sum) with the input command, and consequently a very small input signal would cause the high gain actuator output to fully extend (or retract). Tests were conducted by opening the feedback path of channel A_C (fig. 7) and introducing a ramp command into all channels.

A *passive* failure is a failure condition caused by an open circuit in the input signal path to one or more of the six active/standby channels. The result is that no input commands are available to the affected channel. A feedback signal was available as an input error signal. Tests were conducted by opening the signal path to channel A_C (fig. 7) and introducing a ramp command into all channels.

Failure Sensitivity—Slowover: Table 13 summarizes the output transient (due to a slowover failure) sensitivity to parameter variations, as per table 9.

With the exception of Backlash and friction, none of the study parameter variations noticeably altered the slowover failure output transient of ±5% (f.s.). For Backlash values of 5.1×10^{-5} m and 2.54×10^{-4} m (0.002 in. to 0.010 in.) to failure transient was ±5% and ±8% (f.s.), respectively (fig. 75). Backlash, B, represents mechanical slop in the system. Thus, whenever a slowover failure is detected, the active channel would become disengaged and control switched to a standby channel. The output would then be driven to the position commanded by the activated standby channel. Under these conditions, the system inertia coupled with backlash would result in an overshoot within the limits of the backlash, Thus, the greater the backlash, the greater the overshoot.

The most significant output transients were shown to occur whenever a channel failure was coupled with a position offset of a standby channel (table 14). The reason is that upon failure, a standby channel becomes active, and the position output will be commanded to a new null position (i.e., position offset), different from the old null position.

Failure Sensitivity--Oscillatory, Step, High Gain, and Passive: Tables 15 and 16 summarize the oscillatory, step, and high gain, and passive failure output transient data, respectively. In general (exceptions were the passive failure and high gain), the output would follow a failure command up to the failure detection threshold level. At this level, the failure monitor would disengage the erroneous channel. The output would then move (viz. transient) to the position commanded by the newly activated standby channel. If either the active channel or the activated standby channel was offset from the actual (correct) command signal, a larger (or smaller) output transient could be expected.

Output transient characteristics were determined for the oscillatory failure condition with no specific oscillatory failure logic incorporated into the failure monitor system. However, very low frequency oscillatory failures were detected as a slowover failure. The 0.1 Hz and 1 Hz sinusoidal oscillatory failures of ±10% command level amplitude were detected as slowover failures. The higher frequency (e.g., 10 Hz) oscillatory failures showed output transient amplitudes to be reduced (as compared to lower frequency) because of the system frequency response characteristics (table 15). A channel failure was not detected for the ±10%, 10 Hz signal because the time delay trip level of the failure monitor was set too long. That is, the failure detect signal amplitude was greater than the failure threshold for a period that was shorter than the failure detect time delay.

The output transient characteristics for step failures were predictable. The output transient for a 1% step (f.s.) and no voltage offsets was about 1.5%. Backlash in the actuator model affected the output transient amplitude, particularly at the lower level step commands. The output transient for a 10% step (f.s.) under similar conditions was 10%. Table 16 summarizes the step failure data. When offset commands were introduced among channels, an asymmetric output transient occurred. The noted asymmetry difference was because the offset would either add to or subtract from the output transient depending on the sense at the time of failure detection and switching.

Output transients for the high gain failure ranged from 3% (f.s.) to 10% (f.s.) for conditions of zero offset and 2.5% offset of the standby channel, respectively (table 17).

The output transients for the passive failure condition ranged from 3% (f.s.) to 8% (f.s.) for a zero offset and a 2.5% offset of the standby channel, respectively (table 17).

Failure Sensitivity—Performance Degradation: In an active/standby system, the control channels operate independently with only one channel controlling at a time. There is no force (or load) sharing among channels, and failure of an active channel causes transfer to a correctly operating standby channel with no subsequent performance degradation.

3.4.1.4.2 Force Summed Test Results.—A block diagram of the force summed system is shown in figure 8 to facilitate the discussion of failure types and failure test procedures. The force summed system, as tested, utilized a failure monitoring system as described in paragraph 3.4.1.1. Although not optimized, this failure monitoring system is suitable for comparative evaluation with the active/standby system.

Failure Definition and Test Procedure: The following discussion defines the types of failures and the test procedure used in determining the effects of, and sensitivity to certain failure conditions.

A *slowover* failure is an erroneous signal into one or more of the four force summed channel (fig. 8). Tests were conducted by introducing a ramp command signal into channel A. All other channels received only feedback information and consequently these channels opposed any action by channel A. In addition to determining the transient behavior of the nominal actuator design due to a slowover failure, certain design parameters, table 11, were varied to show the system failure sensitivity to parameter variations.

An *oscillatory* failure is an erroneous periodic signal (e.g., sinusoidal) into one or more of the four force summed channels (fig. 8). These tests were conducted by introducing a sinusoidal command into channel A. All other channels received only feedback information and consequently these channels opposed any action by channel A.

A *step* failure is an erroneous signal in the form of a step input command into one or more of the four force summed channels (fig. 5). Tests were conducted by introducing a step input into channel A. All other channels received only feedback information and consequently these channels resisted any action by channel A.

A *high gain* failure results from an open feedback in one or more of the four force summed channels. Consequently no position output information is available for (algebraic sum) comparison with the input command. Thus, a very small input would command the high gain actuator to fully extend (or retract). Tests were conducted by opening the position feedback to channel A (fig. 8), then introducing a ramp into all four channels.

A *passive* failure is caused by opening the input command path to one or more of the four force summed channels. Tests were conducted by opening the input command path to channel A (fig. 8) then introducing a ramp into all four channels. As a result, channel A receives only feedback information and opposes any action of the other three channels.

Failure Sensitivity–Slowover: Table 18 summarizes the slowover failure transients and transient sensitivity to parameter variations, as per table 11.

Backlash, B, affected the system failure output transient. The output transient varied from 1.8% (f.s.) to 2.4% for B values of 5.1×10^{-5} m to 2.54×10^{-4} m (0.002 in. to 0.010 in.), figure 76. Whenever the failure was detected as a failure and the respective channel disengaged, the output rapidly repositioned to the commanded position by the remaining operable channels. The system inertia coupled with backlash caused the actuator output to overshoot the commanded position. The amount of overshoot (transient) was dependent on the amount of backlash.

Increased friction caused a decreased failure transient. Friction absorbed energy from the system and acted as coulomb damping. Consequently, increased friction caused a decreased output failure transient.

Failure Sensitivity–Oscillatory, Step, High Gain, and Passive: Tables 19, 20, and 21 summarize the oscillatory, step, high gain, and passive failure output transient data. For each of the failure conditions, test data showed that the system output tended to follow the failure command signal at a reduced level because of interchannel force fight.

There was no oscillatory failure logic incorporated into this system. However, very low frequency oscillatory failures were detected as a slowover failure. The 10 Hz output transients showed a large amplitude reduction (larger than 0.1 Hz or 1.0 Hz) (table 19) because of the frequency response characteristics of the system. Position offsets had little effect on the magnitude of the oscillatory output transients, since no channels disengaged for the tested oscillatory failure inputs. Furthermore, whenever an oscillatory failure was introduced into the system with one disengaged channel, the oscillatory output transients were of similar magnitude to the transients of a fully operative system. The reason was that the centering detent spring, which engaged as channel disengagement occurred, provided a load that opposed the oscillatory failure transient. Thus no increased failure transient with respect to channel disengagement was produced.

Step failure data (table 20) showed an attenuated position output, because of interchannel force fight. The ±10% (f.s.) step commands were not large enough to cause channel disengagement.

High gain failure output transients (table 21) were about 2.3% (f.s.). Any position of voltage offset caused the high gain actuator to move at the maximum velocity until a channel failure was detected. The large output transient was due to the finite time delay, which was incorporated into the failure detection logic.

The *passive* failure output transient (table 21) ranged to 1.2% (f.s.). The passive channel tended to resist the actuator commanded movement, since the feedback signal provided a negative command to the passive channel. The passive failure only prevented an input command, not a feedback error signal, from controlling the passive channel. Upon channel disengagement, the resistance due to the passive channel was eliminated and the system drove toward the commanded position. However, the centering detent force engagement replaced the resistive force of the disengaged channel. Consequently, the observed output transient was proportional to the difference between the centering detent force and the force that was produced by the passive channel failure at the moment of channel disengagement.

Failure Sensitivity—Performance Degradation: Load sharing is a characteristic of the force summed system, and the loading on each channel is dependent upon the loading on the other channels. Consequently, whenever a channel failure and disengagement occurs, the operable channels must share the load which was previously carried by the disengaged channel. Furthermore, a centering detent load is engaged upon channel disengagement which always tends to force the position output toward null (center position). Thus, upon channel disengagement, the remaining operable channels must also carry the load of the centering detent. As a result of this load sharing characteristic, system performance degradation was observable upon channel disengagement.

Table 22 summarizes the observed performance degradation due to channel failures. All aspects of the system performance (frequency response, transient response, and resolution) showed degradation.

The system frequency response to a ±5% (f.s.), 0.01 Hz sinusoidal command was used as the basis for comparing steady state response characteristics following failures. The steady state output responses was 5%, 4%, and 2.5% for zero, one, and two channel disengagement, respectively. The -3 dB cutoff frequency also showed degradation (fig. 77).

The system hysteresis losses were 3%, 4%, and 6% (f.s.) for the zero, one, and two channel disengagement (fig. 78). These three plots also show an output versus input gain reduction about null for one and two channel failures. The reason for this attenuated output about null was that the additional system centering detent loads (added as channels are disengaged) absorbed some of the system force capability. However, when the actuators overcame the maximum detent force level, the output to input gain returned to the normal (no load) gain (fig. 78). Although the gain returned to normal, the output position had been reduced.

3.4.2 ANALYTICAL EVALUATION

The analytical trade studies compared the two actuator concepts relative to safety reliability, malfunction reliability, survivability/vulnerability, and system implementation. The purpose of this study was to compare the two concepts relative to these criteria.

3.4.2.1 Safety/Maintenance Reliability

There are two general reliability requirements that the flight control system and its actuation components must meet. These are the mean time between noncritical failures and the mean time between catastrophic failures. The MTBF/noncritical is a maintenance indicator. The MTBF/catastrophic is an indicator of the overall operational reliability of the airplane. The MTBF/noncritical, if too short, may cause an unacceptable frequency of dispatch delays or spending a disproportionate amount of time on maintenance compared to flying time. The MTBF/catastrophic indicates the probability of safely completing a flight without catastrophe due to airplane system failures. The general effect of applying redundancy to a flight control system is to improve the catastrophic MTBF value and degrade the noncritical MTBF value.

System reliability can be calculated from a success path diagram. Assume a redundant channel electronic system with perfect channel processor circuitry that always votes out erroneous electronic signals, monitors electronic failures, and isolates failures from redundant electronic channels. Also, assume a perfect actuator failure detection and correction logic circuitry. The success path diagrams for both the active/standby and force summed configurations could be drawn as shown in figure 79. Let λ_A be the failure rate of a single actuator channel which includes the failure rates of all components in the channel plus hydraulic power. Let λ_m be the failure rate of a single monitor (model) channel which includes the failure rates of all components in that channel.

Active/Standby: In the three-channel active/standby system, one channel (actuator plus monitor) is required to ensure a good output or a fail-passive last failure. The reliability of the system can be calculated as follows. The probability of a channel failing in any one flight is approximately *$\lambda_c t$ where t is flight time. The probability of n channels failing would be $(\lambda_c t)^n$; where λ_c is the sum of λ_A and λ_m. Therefore:

$$\lambda_{active/standby} = (\lambda_A + \lambda_m)^3 (t)^3$$

Force Summed: In the four-channel force summed system, two operating channels are required to ensure a good output or a fail-passive last failure. The probability of n channels failing, as before, would be $(\lambda_c t)^n$. The probability of the system failing can be computed

*Probability of failure = $1 - e^{-\lambda t}$ and when λt is small: $1 - e^{-\lambda t} \approx \lambda t$

by summing the probabilities of all the mutually exclusive ways it could fail. An n channel system could fail by having any combination of n-1 channels fail or by having n channels fail. The probability of n-1 channels failing is $(\lambda_c t)^{n-1}$. There are n mutually exclusive combinations for having n-1 channels of an n channel system fail. Thus, the probability of an n channel system failing would be:

$$\lambda_{\text{force summed}} = n(\lambda_c t)^{n-1} + (\lambda_c t)^n$$

since $\lambda_c t$ is much smaller than 0.1 for any practical system, a satisfactory approximation is:

$$\begin{aligned}\lambda_{\text{force summed}} &= n(\lambda_c t)^{n-1}\\ &= 4(\lambda_A t)^3\end{aligned}$$

Conclusions: With the above derived probabilities for system failures, and assuming that $\lambda_A = \lambda_{servo} + \lambda_{hyd}$ is the same for both concepts, and that $\lambda_m = \lambda_{servo}$, the following can be derived:

$$\begin{aligned}\lambda_{A/S} &= (\lambda_{servo} + \lambda_{hyd} + \lambda_m)^3\, t^3\\ \lambda_{FS} &= 4(\lambda_{servo} + \lambda_{hyd})^3\, t^3\end{aligned}$$

Let:

$\lambda_{servo} = 25 \times 10^{-6}$ failures/hour

$\lambda_{hyd} = 250 \times 10^{-6}$ failures/hour

$\lambda_m = 25 \times 10^{-6}$ failures/hour

Then the data of table 23 can be calculated. Figure 80 shows the relationship of total system loss versus duration of flight for both the active/standby and force summed systems.

The number of hydraulic systems used, as well as the failure rate of hydraulic systems relative to other component failure rates has a significant effect on the reliability results. The active/standby, three-channel system is assumed to use three hydraulic systems, whereas the four-channel, force summed system naturally uses four hydraulic systems. This fact, in itself, tends to reduce the relative reliability of the force summed system, i.e., the probability of losing any three hydraulic systems out of four is greater than losing all three out of only three.

During the Boeing/US SST development, it had been established that an "extremely remote" failure probability classification would be equal to or less than one failure in 10^9 flight hours. "Extremely remote" failures are those which, although theoretically possible, would not be expected to occur in the life of an SST fleet.

The reliability calculation of the two actuation concepts of this study are within this range.

3.4.2.2 Survivability/Vulnerability

Because the entire secondary actuator, cylinders, control valves, and summing mechanism can be considered vulnerable, it is assumed that protection would be provided to preserve the integrity of the system in a hostile environment. In-flight damage could result from gunfire, noncatastrophic midair collision, engine burst, tire burst, etc. Since both actuator concepts are approximately the same size, the penalty for protection would be about the same (e.g., if by armor protection).

The vulnerability of hydraulic systems is a significant concern in configurating systems. With the triple-channel, active/standby system only three hydraulic systems are used; therefore, only three hydraulic systems are exposed to a common damaging occurrence. Whereas, with the four-channel, summed system which uses four hydraulic systems, the exposure is greater and the vulnerability of the total airplane system could be more severe. Due to this vulnerability, the force summed system is rated less desirable than the active/standby system in terms of survivability.

3.4.2.3 System Implementation

Producibility.—Both concepts are ranked the same in producibility, i.e., manufacturing and quality assurance. Although somewhat different, neither concept requires any specialized, unique hardware or equipment requiring expensive development of special manufacturing techniques.

Weight.—A weight comparison shows the active/standby actuator system has an advantage over the force summed system, The major difference is due to the number of actuator channels required for each concept; three for the active/standby versus four for the force summed. With a single actuator channel weight of 2.27 kg (5 lb), and an output summing mechanism weight of 4.54 kg (10 lb) for the force summed and 3.63 kg (8 lb) for the active/standby, then the following weight summation results:

	Total actuator weight
Active/standby	10.5 kg (23 lb)
Force summed	13.6 kg (30 lb)

Cost.—The cost breakdown for the two concepts is based on a qualitative comparison since actual costs were not determined. To rate the systems, it is assumed that in the force summed system, each actuator channel costs a specific amount as does the summing mechanism. Then, for the active/standby system, since each channel is the same as a force summed channel, plus a monitor (essentially an electrohydraulic servo valve), each channel would cost about 1.2 times the amount. The active/Standby output summing mechanism cost is about 0.75 times the force summing mechanism. Therefore, the following cost comparison can be calculated.

Force summed

$$4X + X = 5X$$

Summing mechanism

Actuators

Active/standby

$$3(1.2X) + 0.75X = 4.4X$$

Summing mechanism

Actuators

Therefore, the active/standby system costs approximately 0.9 of the force summed system.

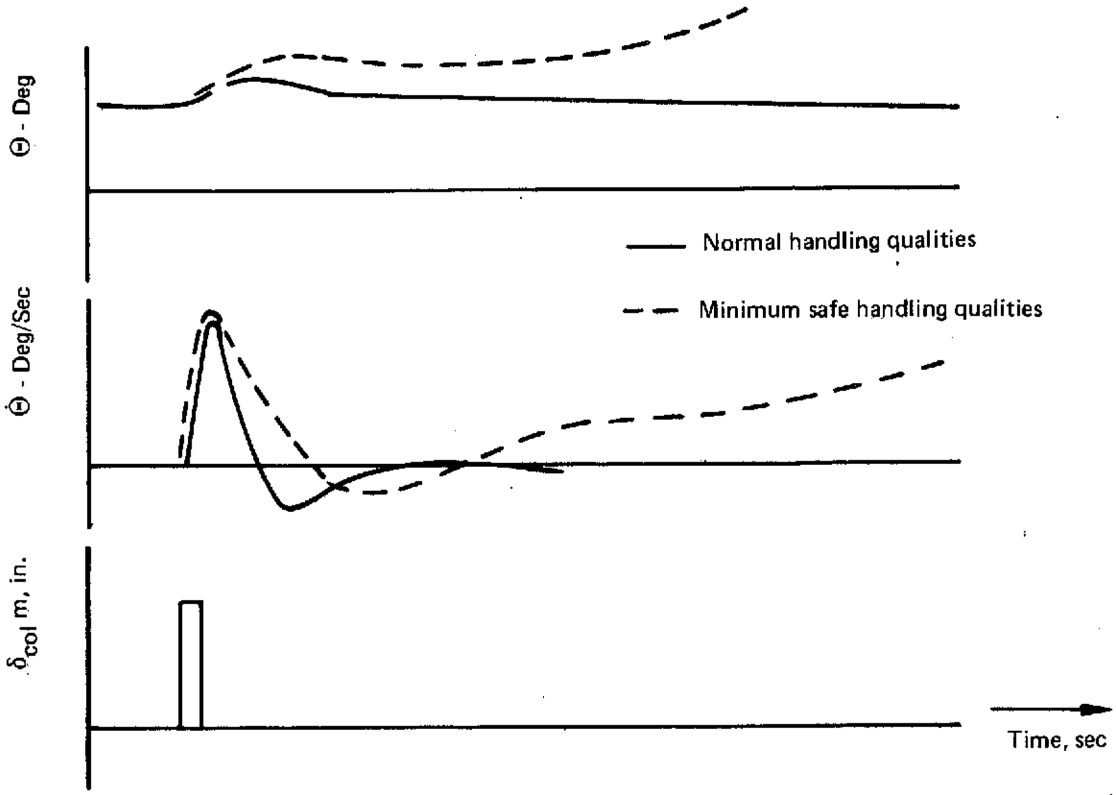


Figure 32.—Summary of Airplane Configuration Characteristics—Landing Approach

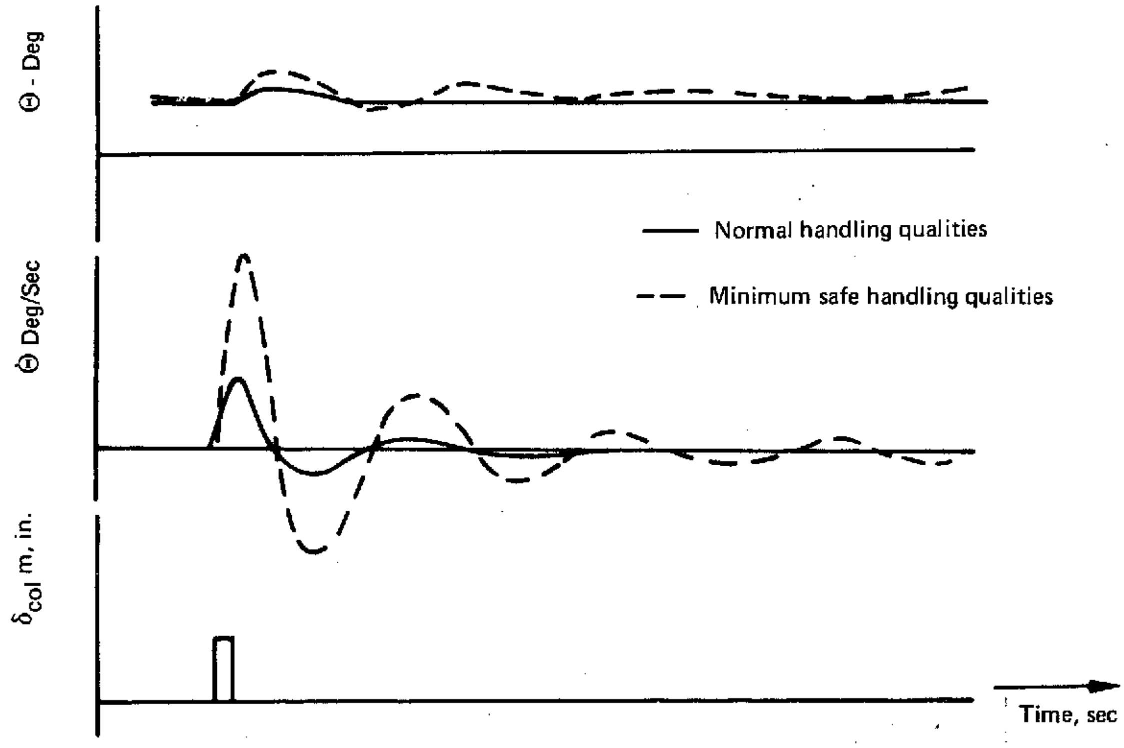
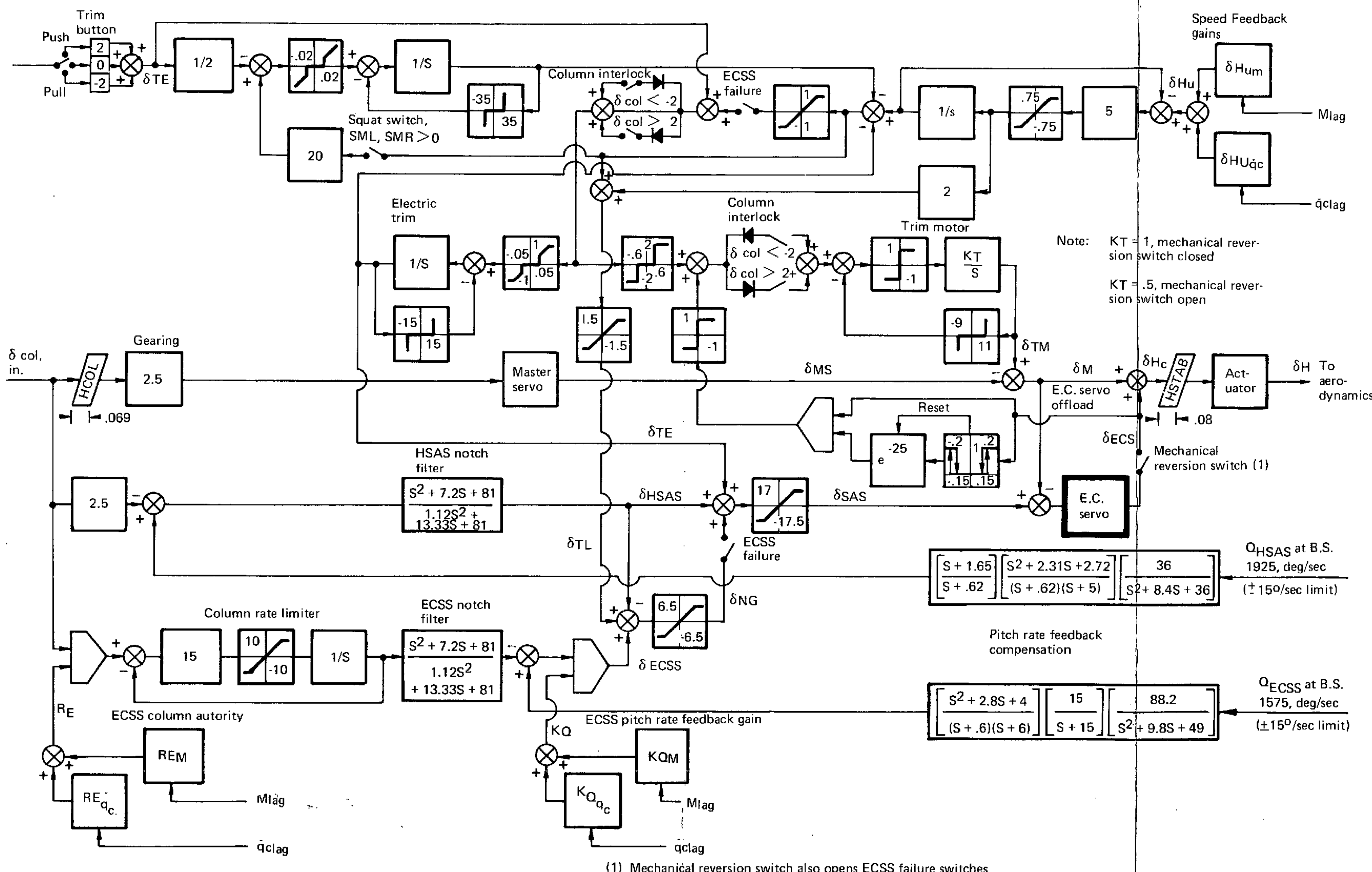


Figure 33.—Summary of Airplane Configuration Characteristics—Cruise (M=2.7)



(1) Mechanical reversion switch also opens ECSS failure switches

Figure 34.—Longitudinal Control System Functional Description

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FOLDOUT FRAME 1

C-2

FOLDOUT FRAME 2

PILOT TASK

Landing approach and touchdown

Check:

- Pitch SAS on
- Roll SAS off
- Yaw SAS on
- Autothrottle engage
- Noise on
- IAS 144 knots
- Altitude 1800 ft
- IVSI 0 ft/min

Perform the following tasks:

- Maintaining constant altitude, capture localizer
- Flying the localizer, capture glideslope
- After stabilizing on localizer and glideslope, deviate one dot above glideslope and stabilize
- Recapture glideslope
- Continue landing to nose-wheel touchdown.

Figure 35.—Sample Pilot Task Description—Landing Approach

PILOT TASK

High-speed cruise maneuvering

Check:

- Pitch SAS on
- Roll SAS on
- Yaw SAS on
- Throttles synchronized
- Noise on
- Mach number reading 2.7
- IAS 567 knots
- Altitude 60,000 ft
- IVSI 0 ft/min

Starting from stabilized level flight condition conduct the following: altitude, airspeed, and heading changes in sequence. Trim airplane for straight and level flight after each maneuver.

Altitude variations:

- Climb to 60,250 ft at 500 ft/min
- Descend to 59,500 ft at 1000 ft/min
- Climb to 60,500 ft at 2000 ft/min
- Descend to 60,000 ft at 500 ft/min

Airspeed variations:

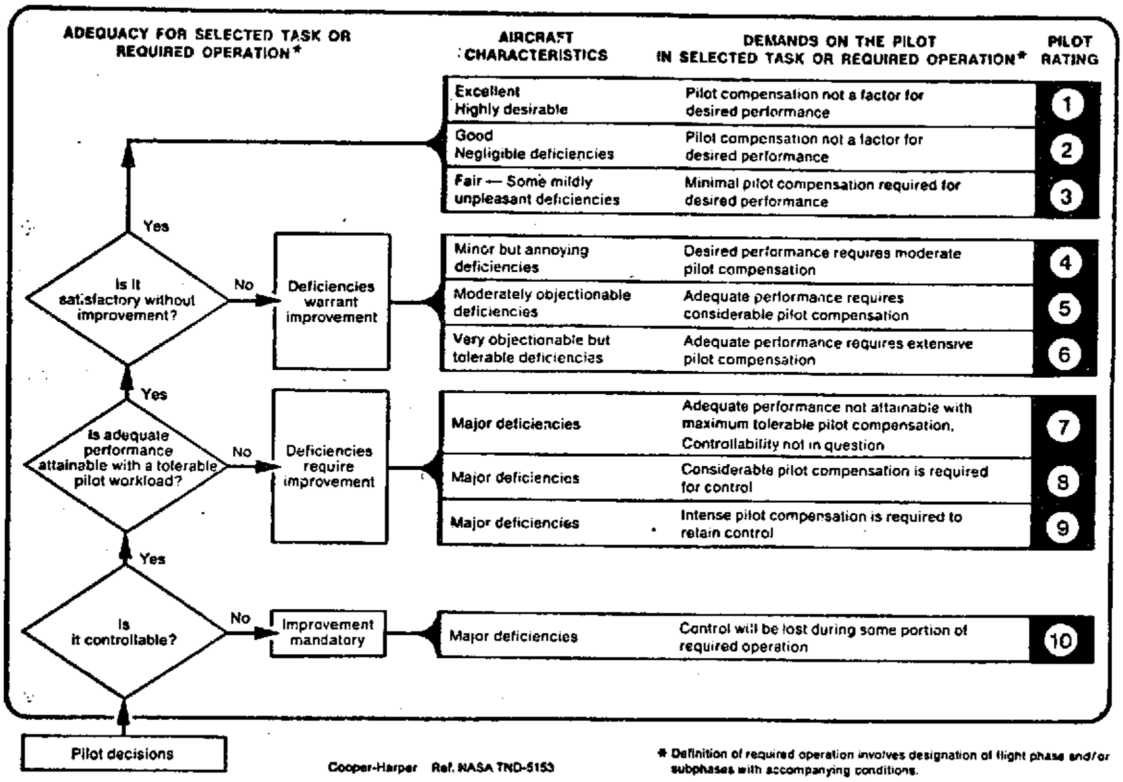
- Increase indicated airspeed to 587 knots
- Decrease indicated airspeed to 547 knots
- Increase indicated airspeed to 567 knots

Heading changes:

- Turn to a heading of 105 degrees — 15 degree bank
- Turn to a heading of 080 degrees — 30 degree bank

Figure 36.—Sample Pilot Task Description—Cruise

HANDLING QUALITIES RATING SCALE



DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft.

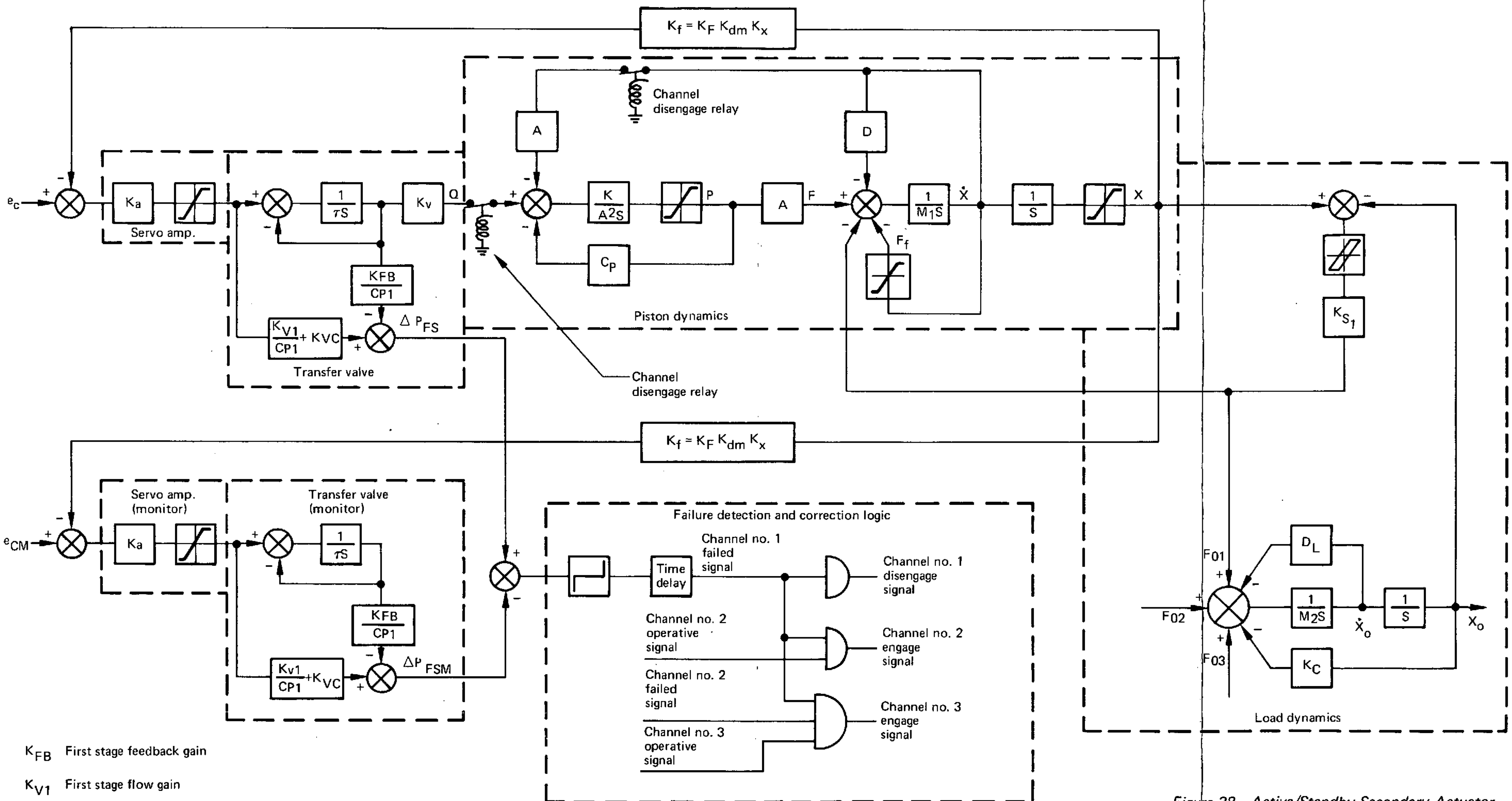
TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task.

Figure 37.—Cooper-Harper Rating Scale



K_{FB} First stage feedback gain

K_{V1} First stage flow gain

K_{VC} Second stage spool centering spring

Figure 38.—Active/Standby Secondary Actuator-Analog Model Block Diagram (One Channel Shown)

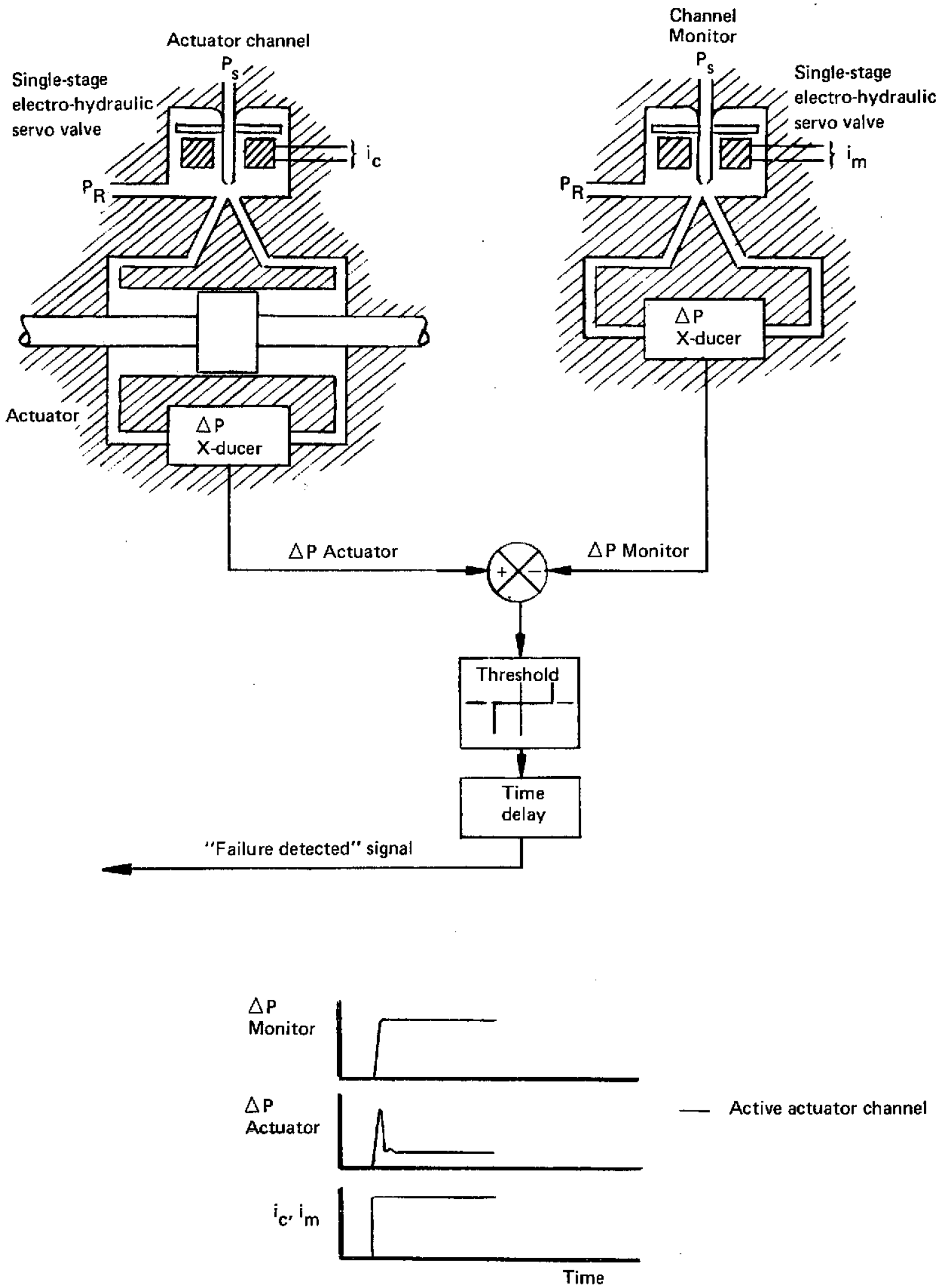


Figure 39.—Active/Standby Configuration 1 Monitor Schematic

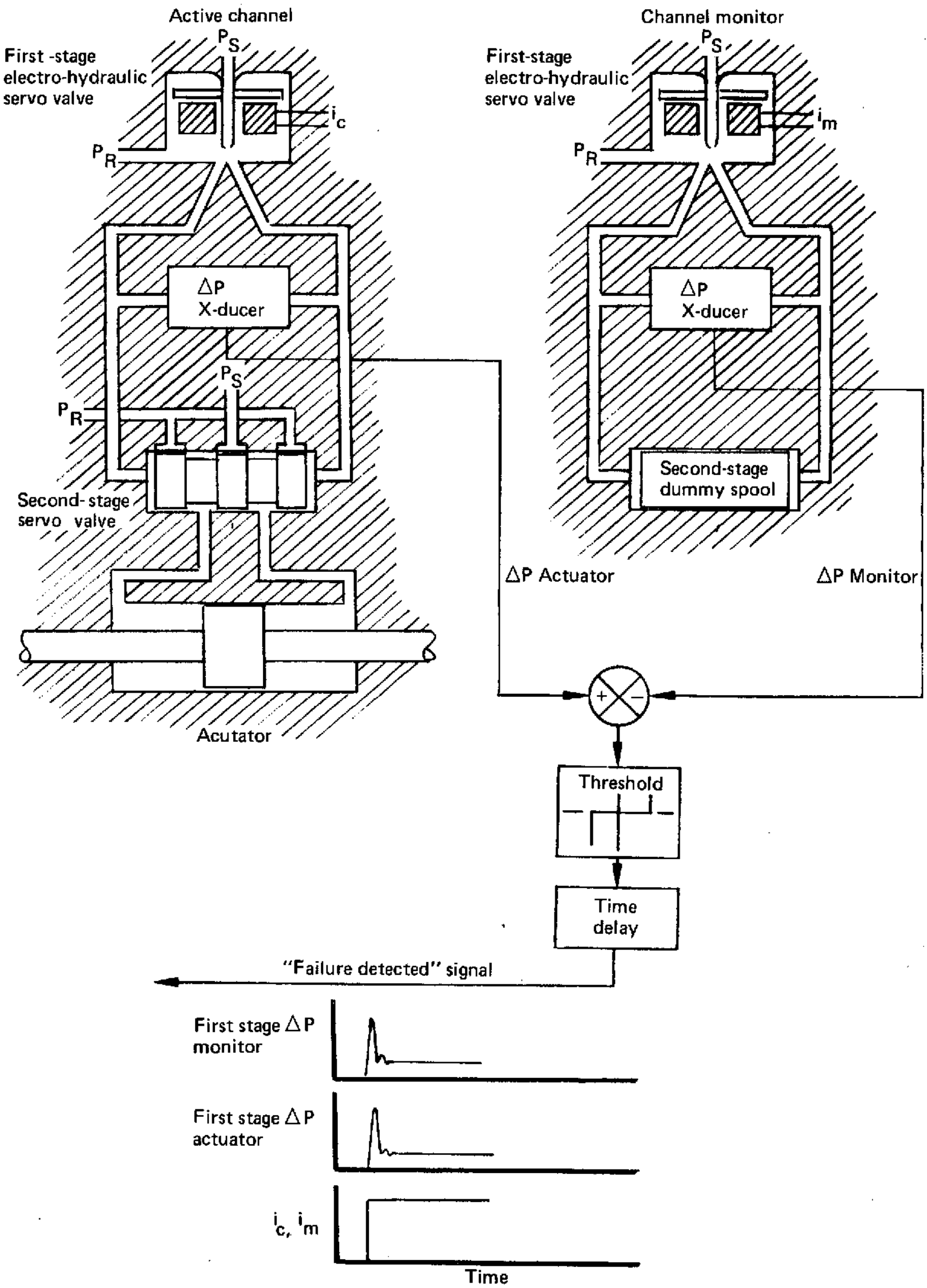


Figure 40.—Active/Standby Configuration II Monitor Schematic

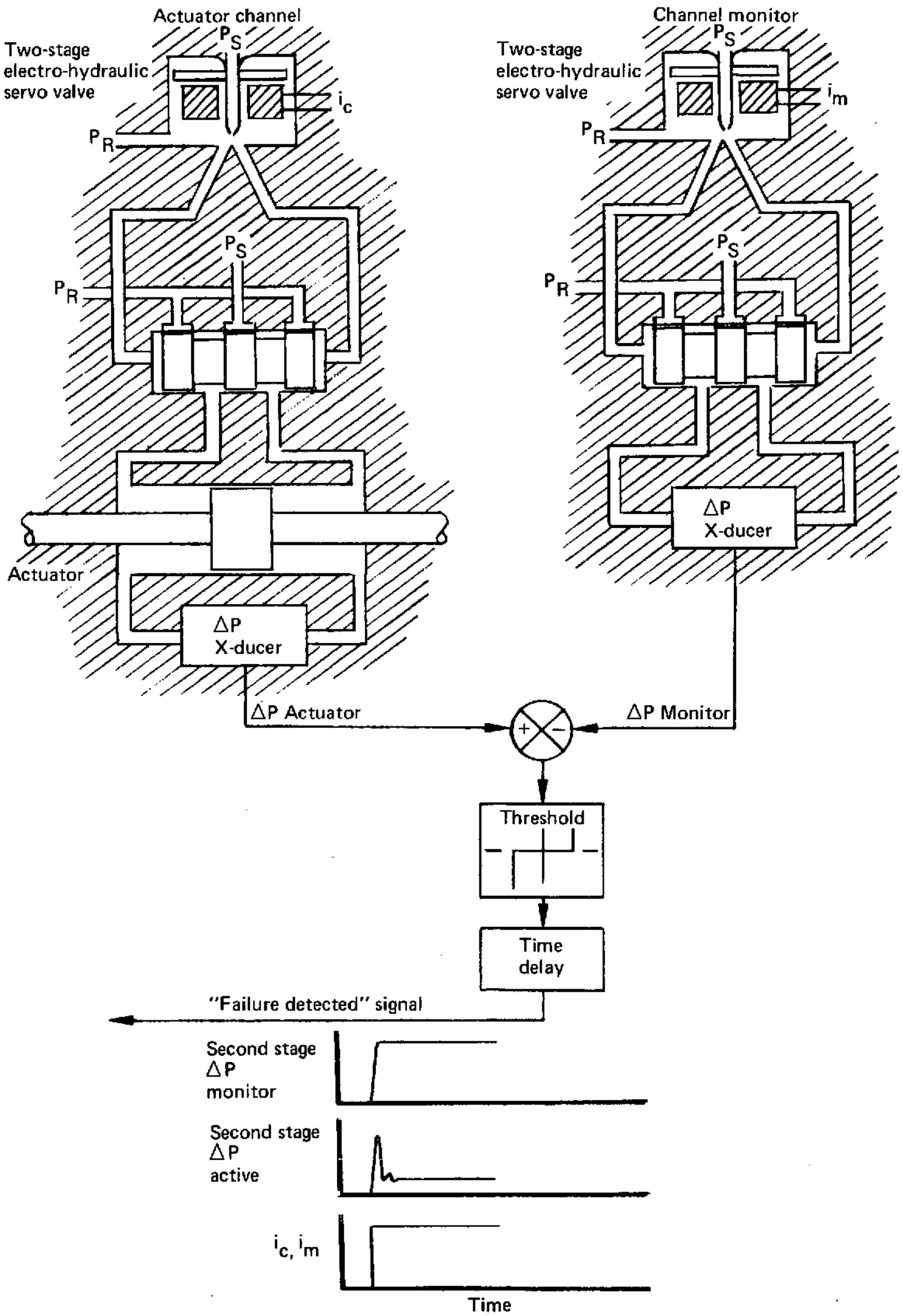
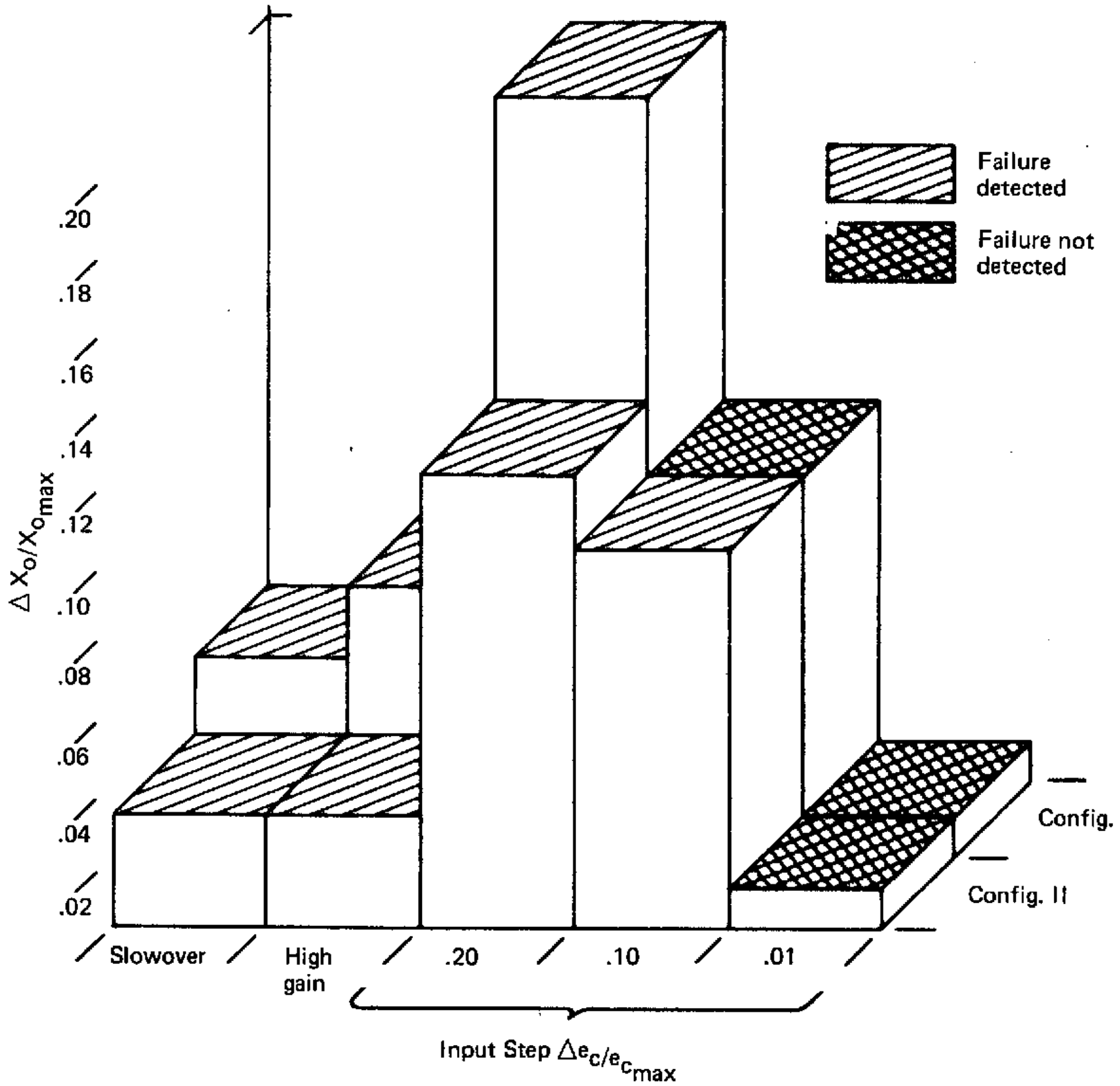


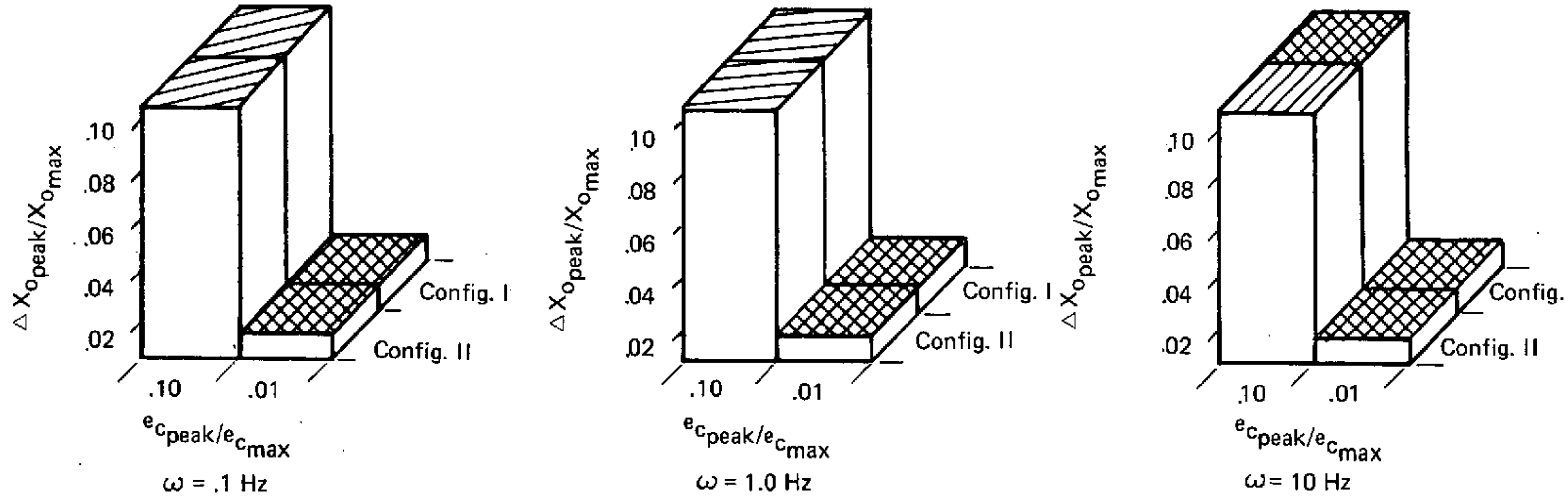
Figure 41.—Active/Standby Configuration III Monitor Schematic



Failure transient $\Delta X_o/X_{o_{max}}$

Failure mode	Configuration	
	I	II
Slowover	0.05	0.03
High gain	0.07	0.03
Step $\Delta e_c/e_{c_{max}} = 0.01$	0.01	0.01
Step $\Delta e_c/e_{c_{max}} = 0.10$	0.10	0.10
Step $\Delta e_c/e_{c_{max}} = 0.20$	0.20	0.12

Figure 42.—Active/Standby Valve/Monitor Configuration Selection Failure Transient Summary



Failure mode	Configuration I	Configuration II
Oscillatory, $e_{c_{peak}}/e_{c_{max}}$ = .10, ω = .10 Hz	FD	FD
Oscillatory, $e_{c_{peak}}/e_{c_{max}}$ = .01, ω = .10 Hz	FND	FND
Oscillatory, $e_{c_{peak}}/e_{c_{max}}$ = .10, ω = 1.0 Hz	FD	FD
Oscillatory, $e_{c_{peak}}/e_{c_{max}}$ = .01, ω = 1.0 Hz	FND	FND
Oscillatory, $e_{c_{peak}}/e_{c_{max}}$ = .10, ω = 10. Hz	FND	FD
Oscillatory, $e_{c_{peak}}/e_{c_{max}}$ = .01, ω = 10. Hz	FND	FND

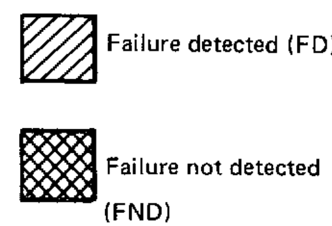


Figure 43.—Active/Standby Valve/Monitor Configuration Selection Oscillatory Failure Summary

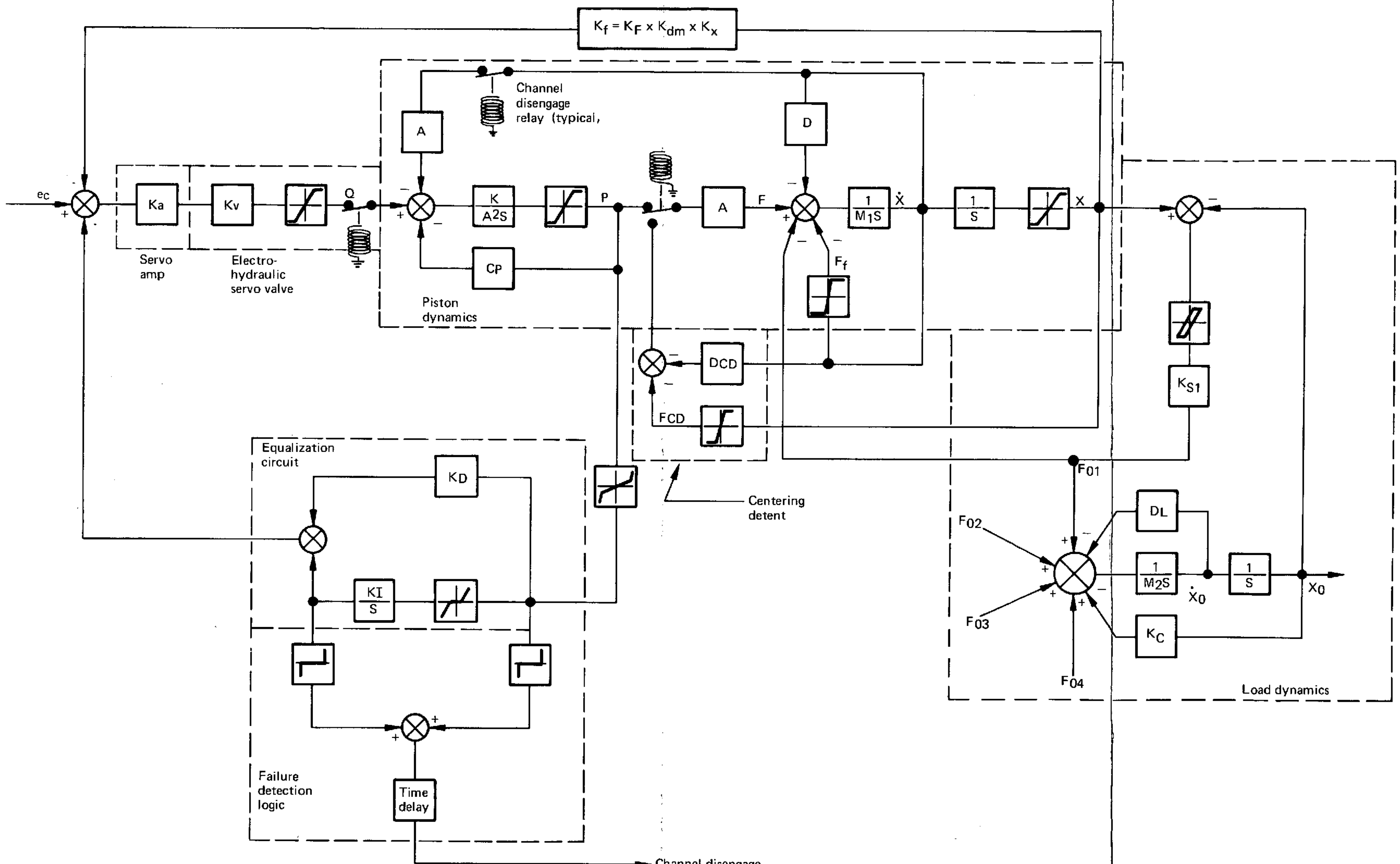


Figure 44.–Force Summed Secondary Actuator Analog Model Block Diagram (One Channel Shown)

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

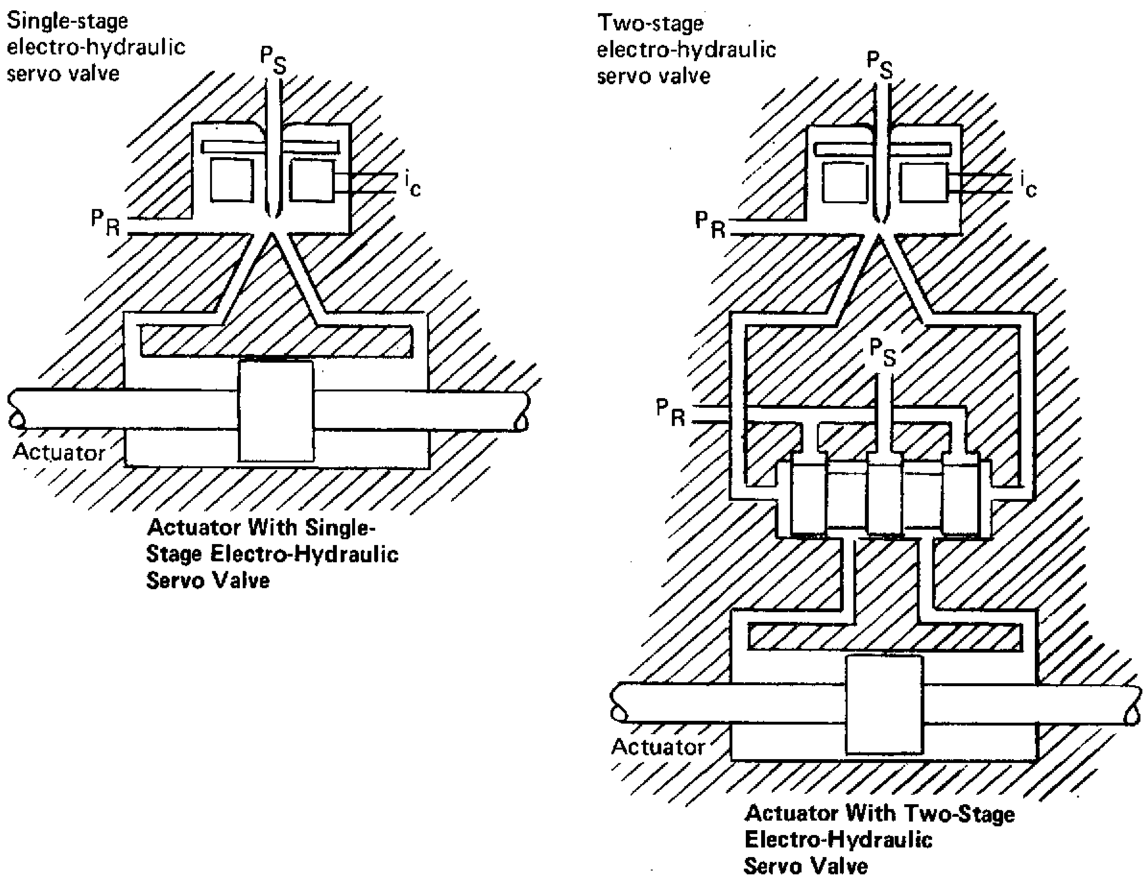

Figure 45.—Force Summed Servo Valve Configuration Schematics

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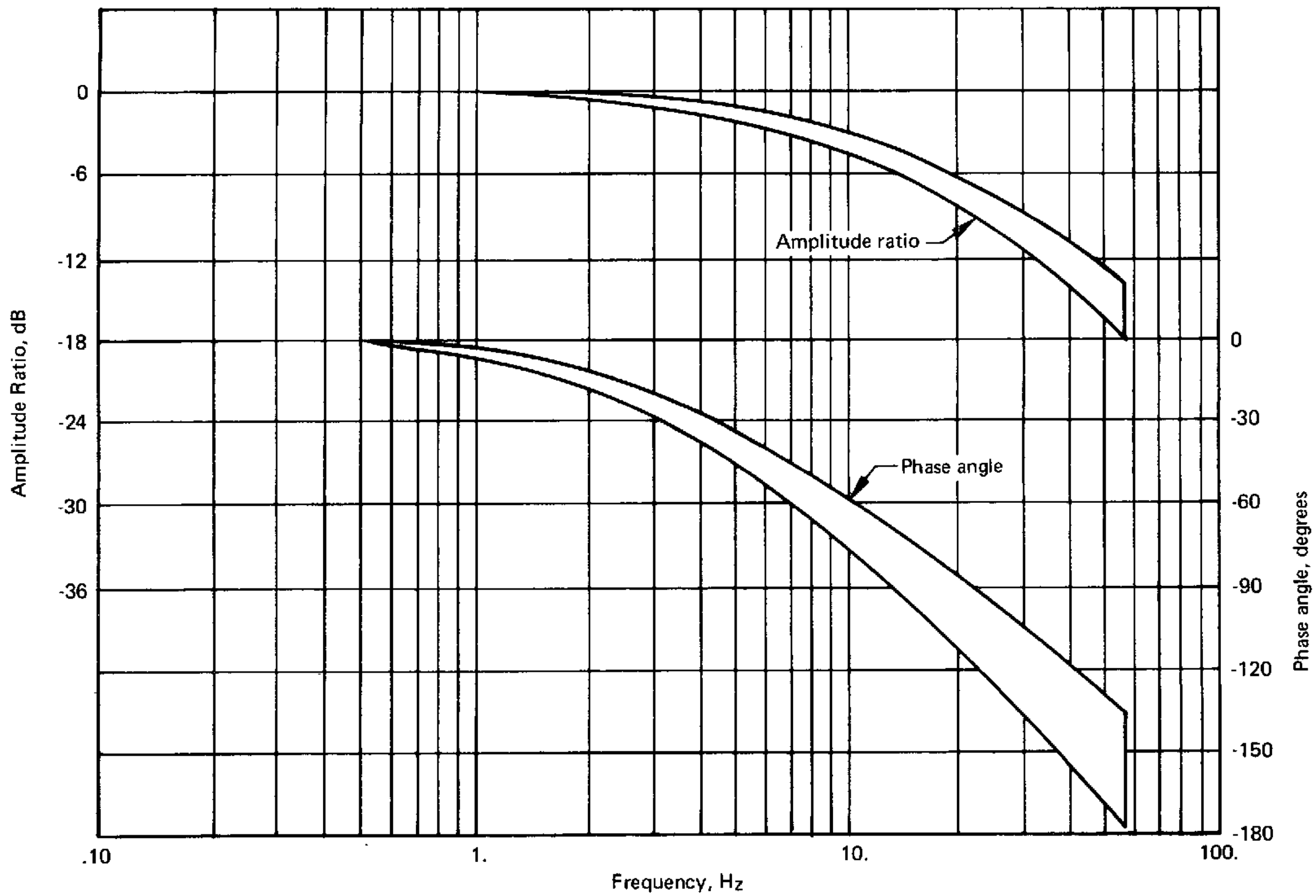
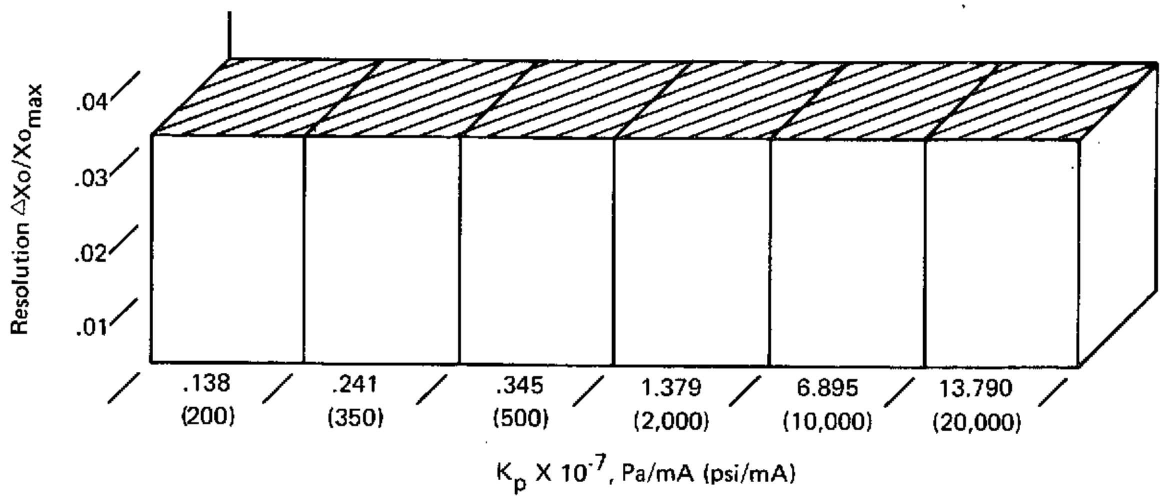
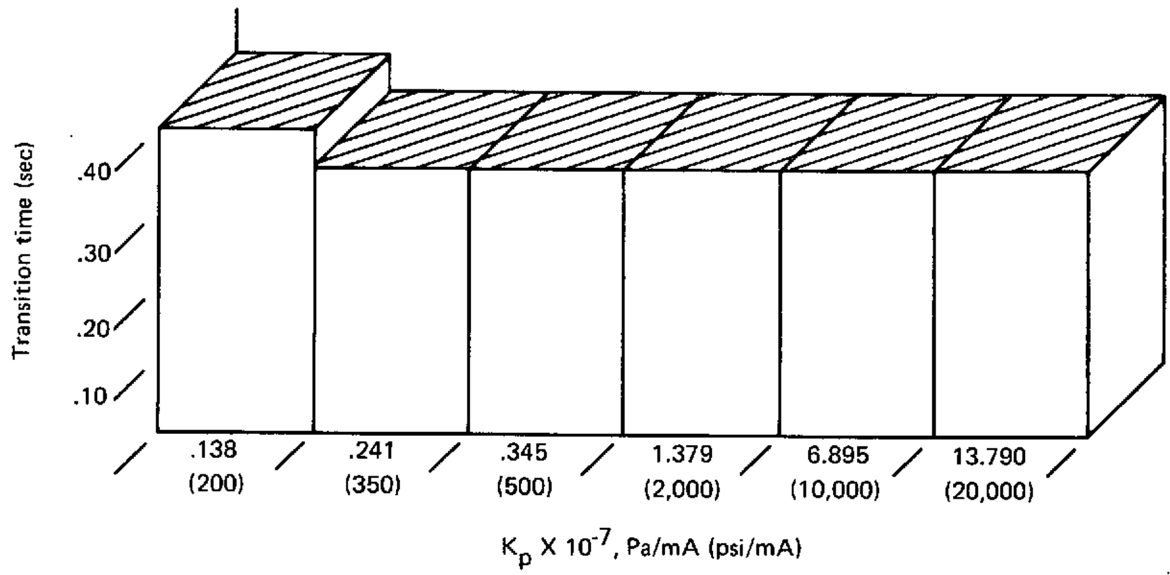


Figure 46.—Force Summed Valve Configuration Selection Frequency Response Summary, Normal Performance





Performance parameter	Valve pressure gain (K_p) × 10^{-7}, Pa/mA					
	0.138	0.241	0.345	1.379	6.895	13.790
Transition time, sec	0.40	0.35	0.35	0.35	0.35	0.35
Resolution $\Delta X_o/X_{o_{max}}$	0.03	0.03	0.03	0.03	0.03	0.03

Figure 47.—Force Summed Valve Configuration Selection, Resolution and Transient Test Summary, Normal Performance

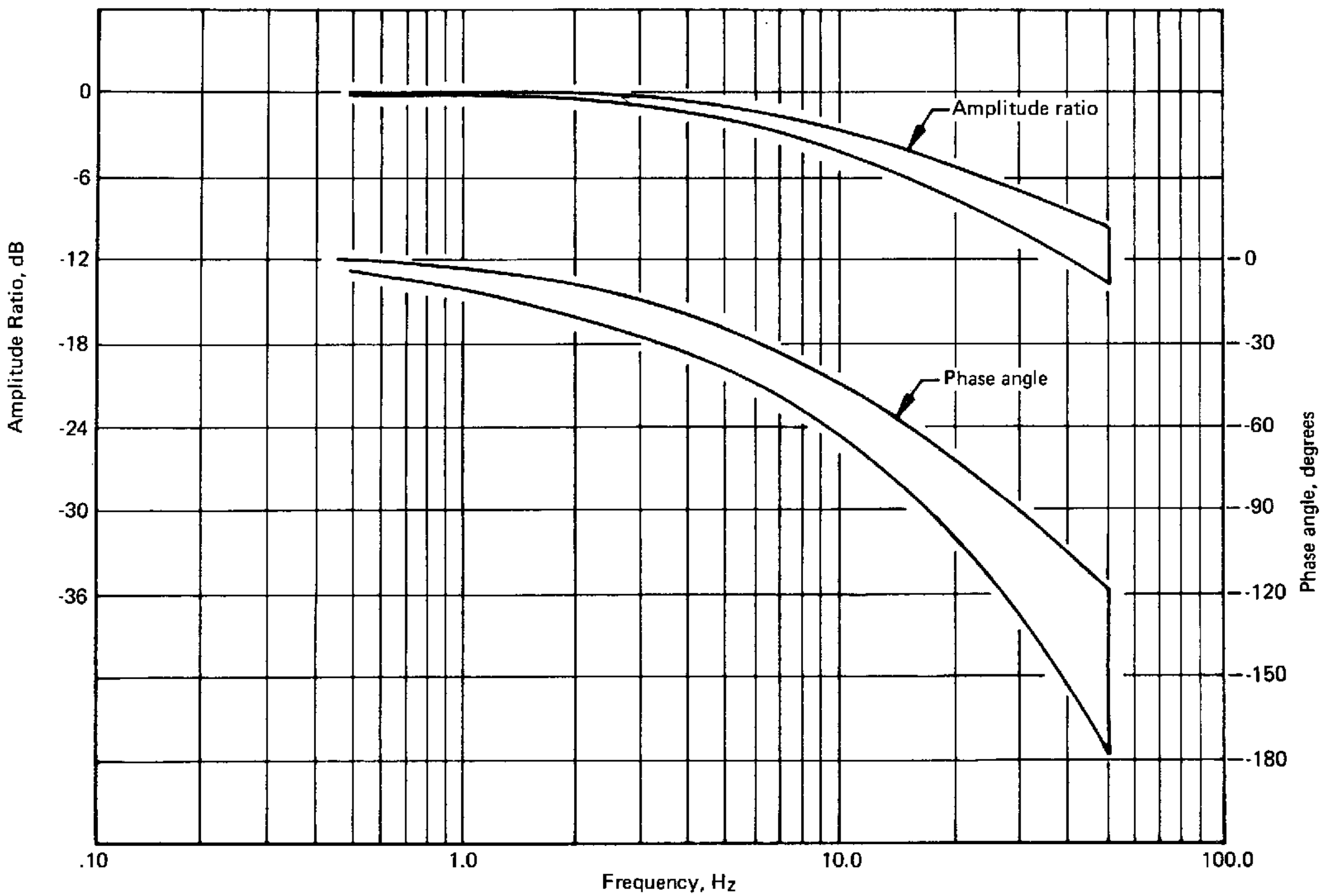
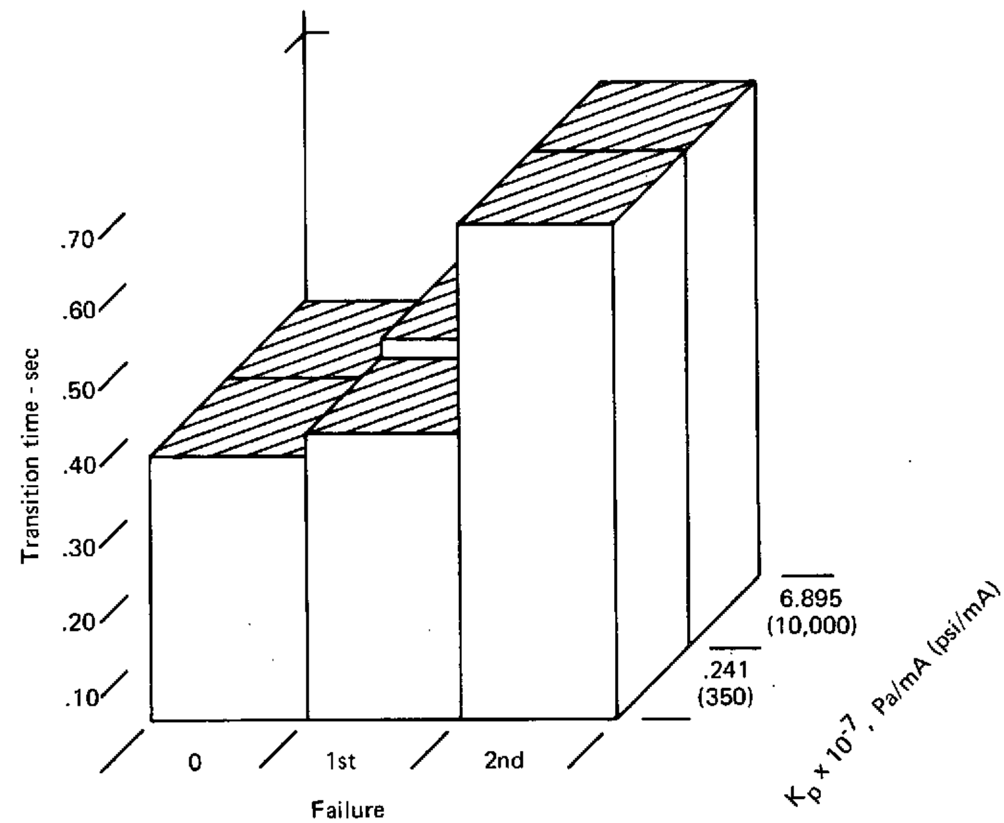
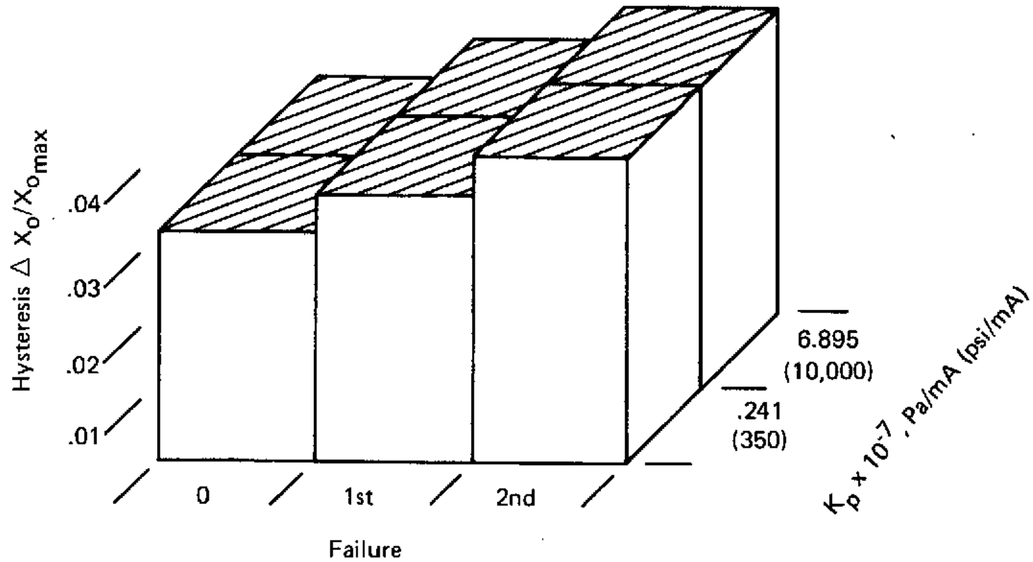


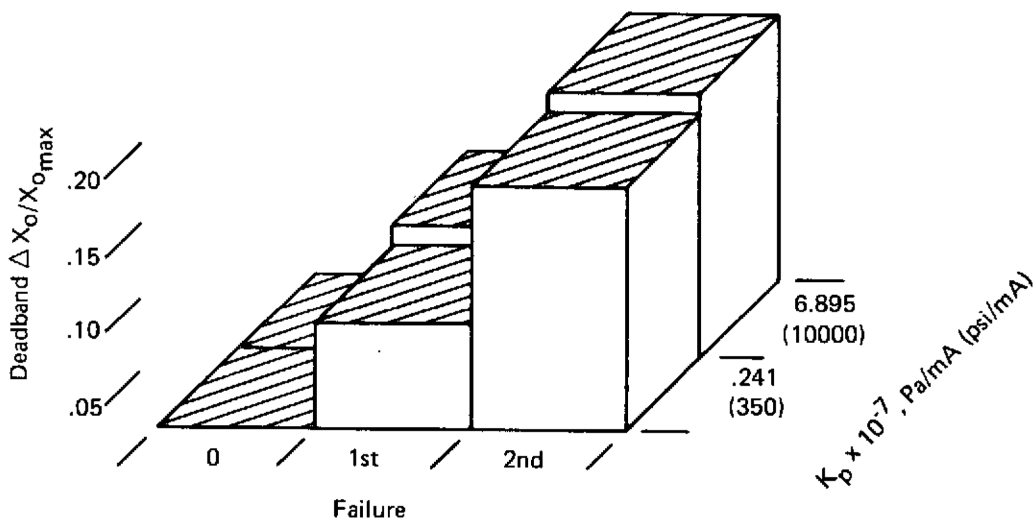
Figure 48.—Force Summed Valve Configuration Selection, Frequency Response Test Summary, One and Two Channel Failures



Failure mode	Valve pressure gain (K_p) x 10^{-7}	
	6.895 (Pa/mA)	0.241 (Pa/mA)
No failure	0.35 (sec)	0.35 (sec)
One channel failed	0.040 (sec)	0.375 (sec)
Two channels failed	0.65 (sec)	0.65 (sec)
	Transition times	

Figure 49.—Force Summed Valve Configuration Selection, Transient Test Summary, One and Two Channel Failures





Failure mode	Valve Pressure gain (K_p) x 10^{-7}			
	6.895 (Pa/mA)		0.241 (Pa/mA)	
	Hysteresis $\Delta X_o/X_{o_{max}}$	Deadband $\Delta X_o/X_{o_{max}}$	Hysteresis $\Delta X_o/X_{o_{max}}$	Deadband $\Delta X_o/X_{o_{max}}$
No failure	0.03	0.0	0.03	0.0
One channel failed	0.035	0.08	0.035	0.07
Two channels failed	0.04	0.17	0.04	0.16

Figure 50.—Force Summed Valve Configuration Selection Resolution Test Summary, One and Two Channel Failures

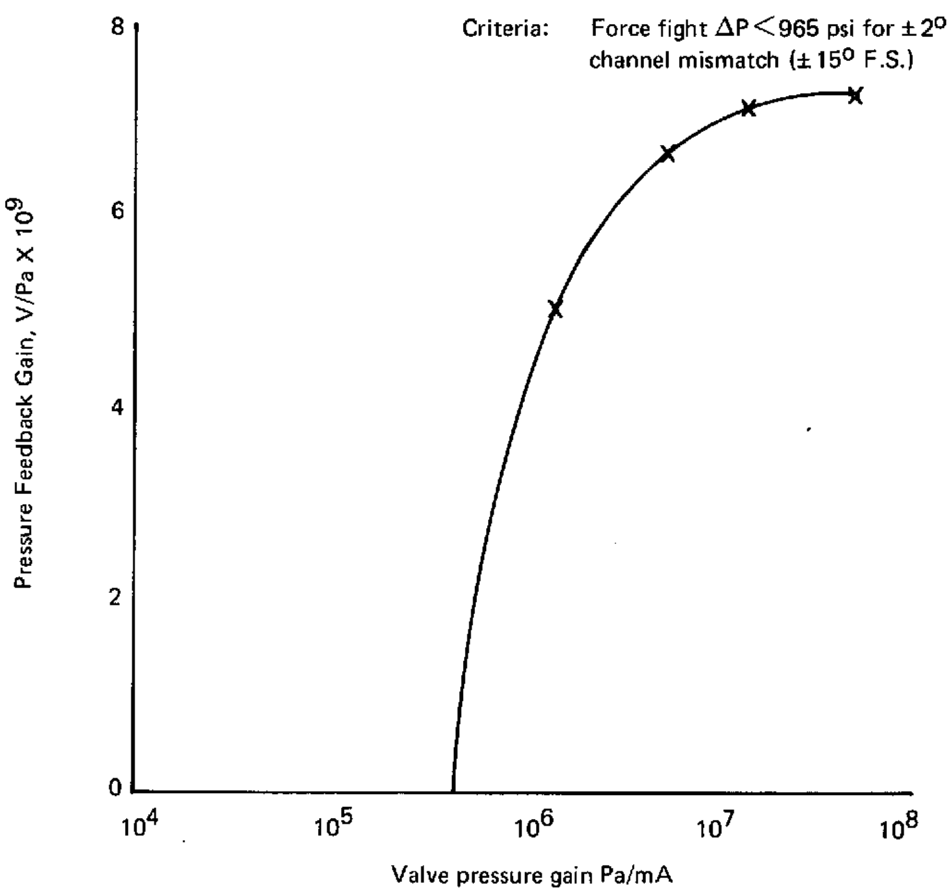


Figure 51.—Pressure Feedback Gain Versus Valve Pressure Gain for Force Summed Concept

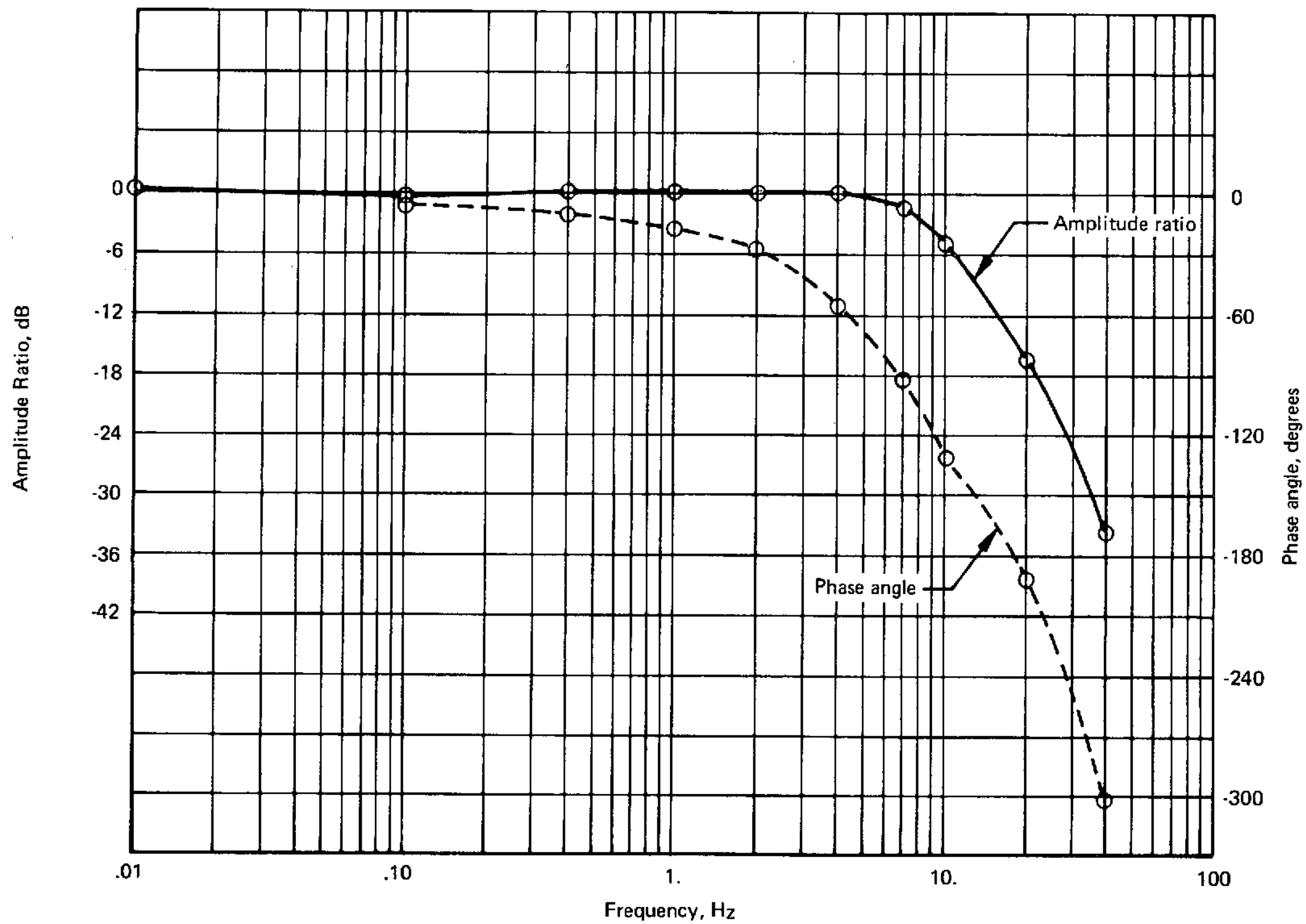


Figure 52.—Frequency Response, Active/Standby

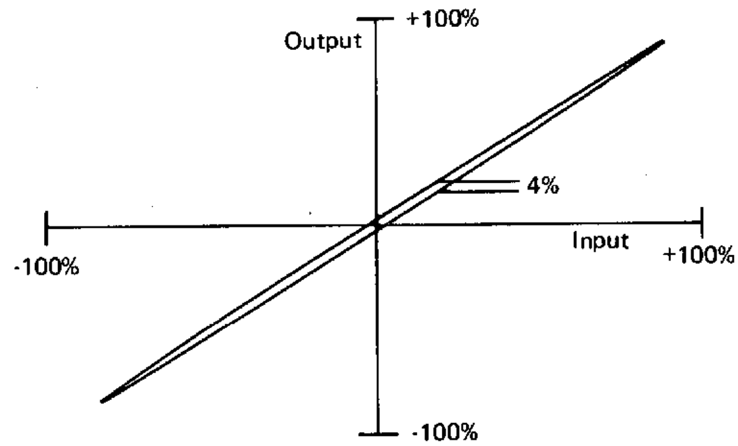


Figure 53.—Resolution, Active/Standby, Normal Operation

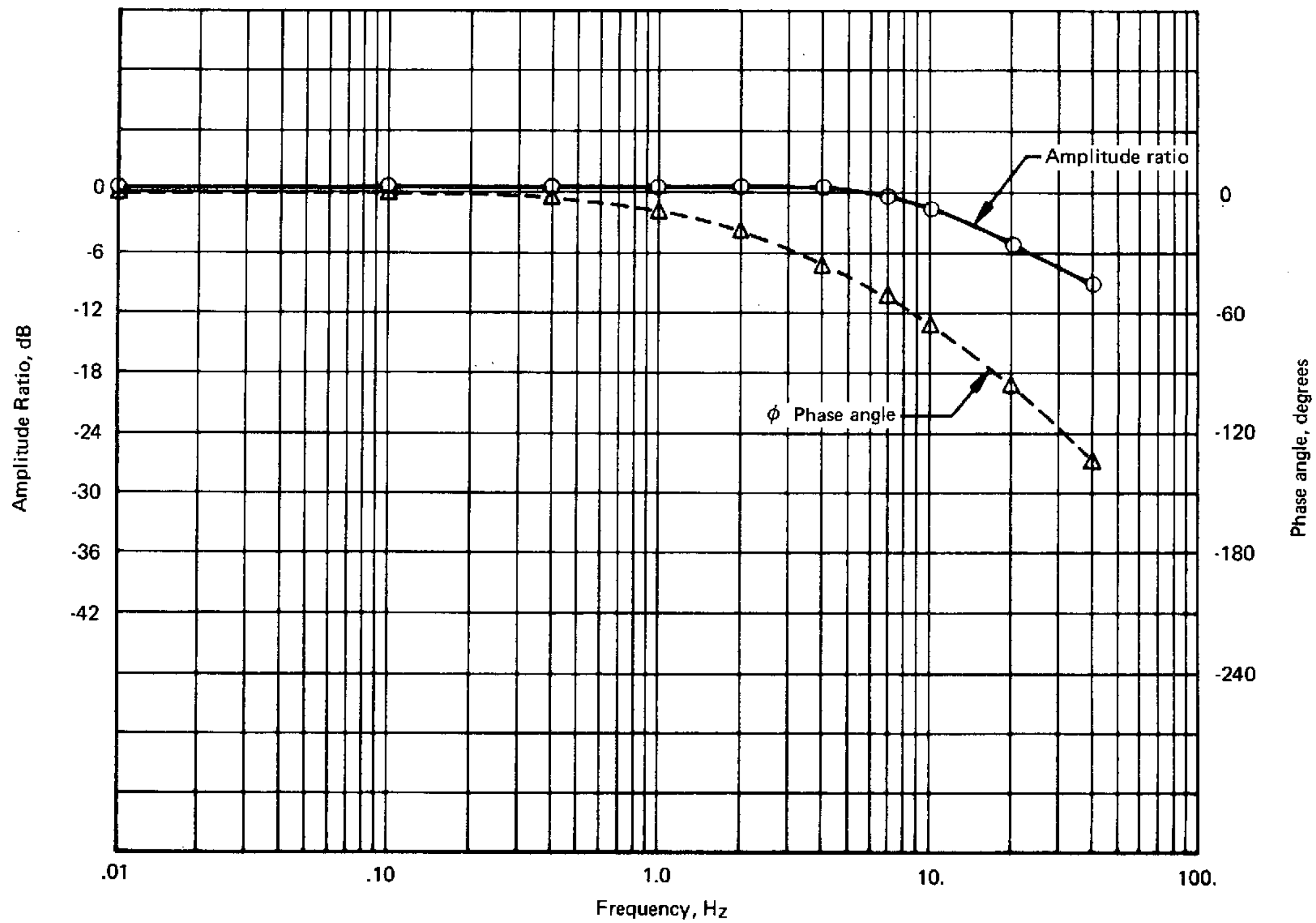


Figure 54.—Frequency Response Force Summed, Normal Operation

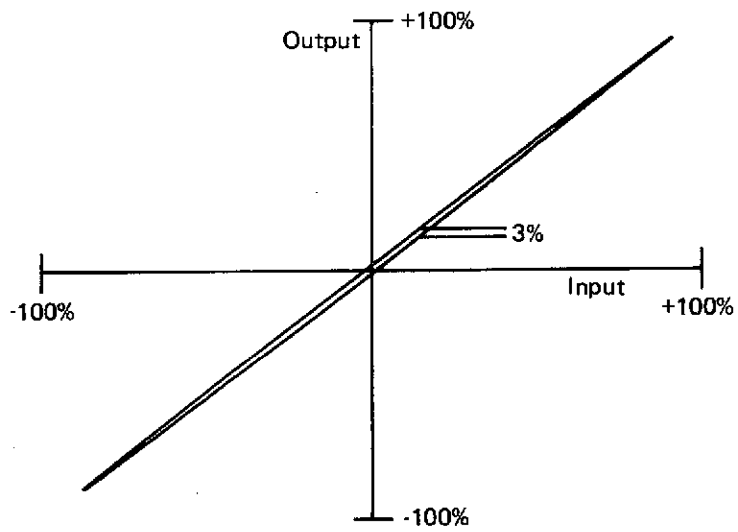


Figure 55.—Resolution, Force Summed, Normal Operation

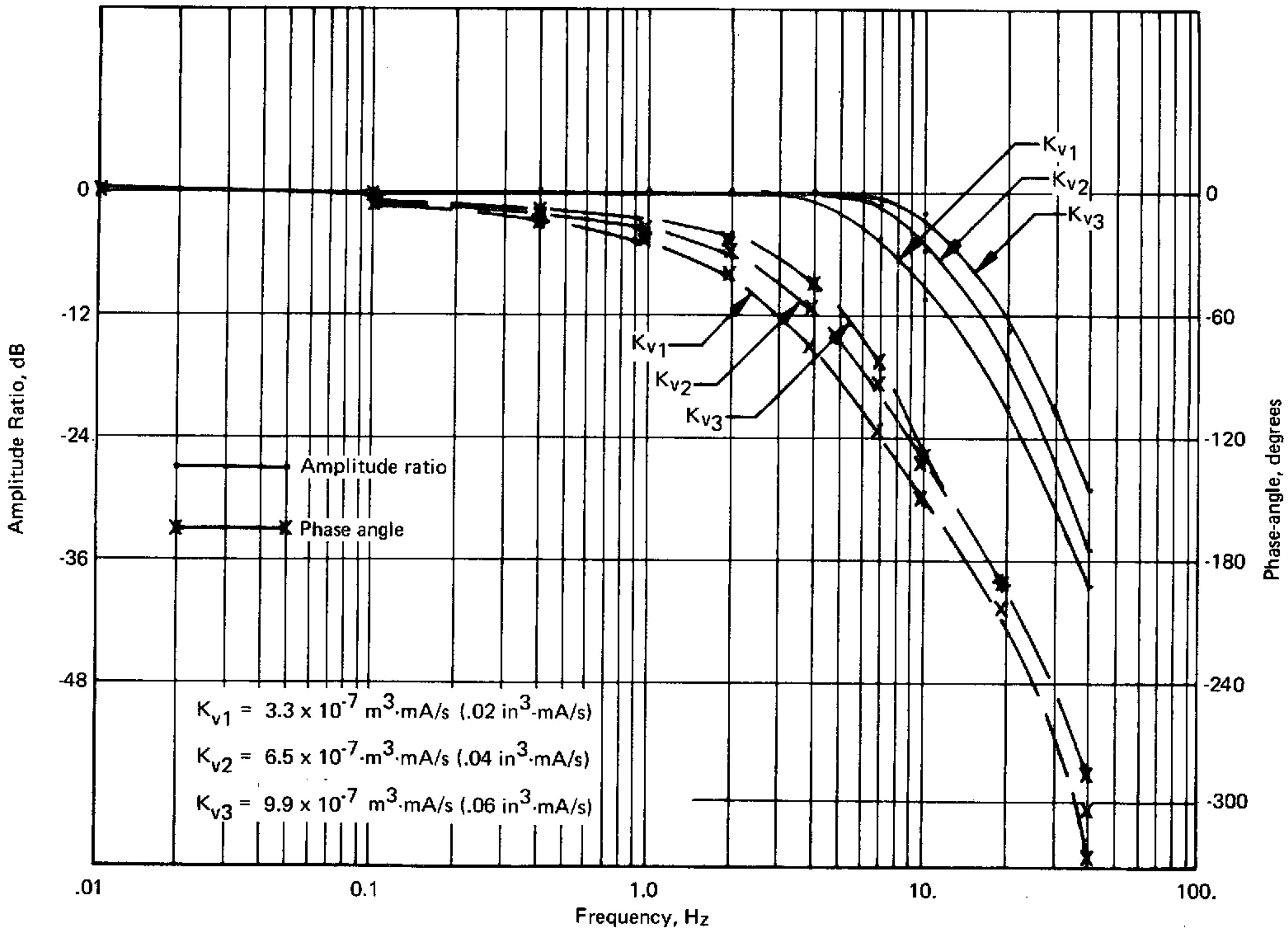


Figure 56.—Active/Standby Flow Gain Sensitivity, Frequency Response

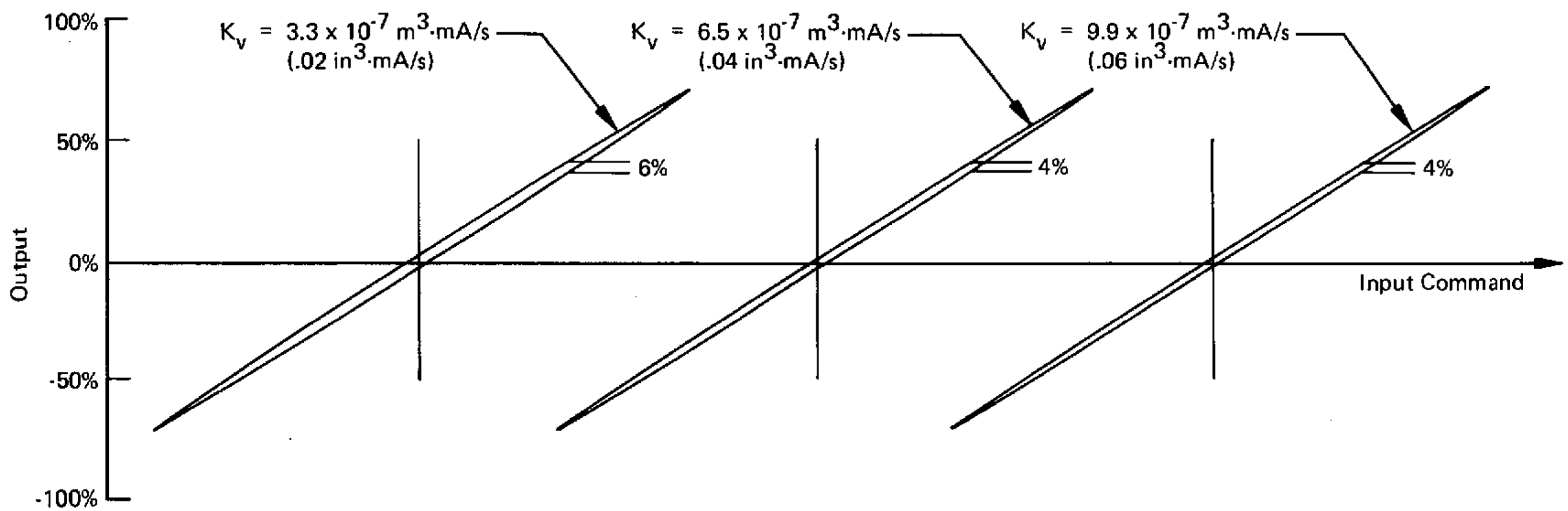


Figure 57.—Active/Standby, Flow-Gain Sensitivity, Resolution

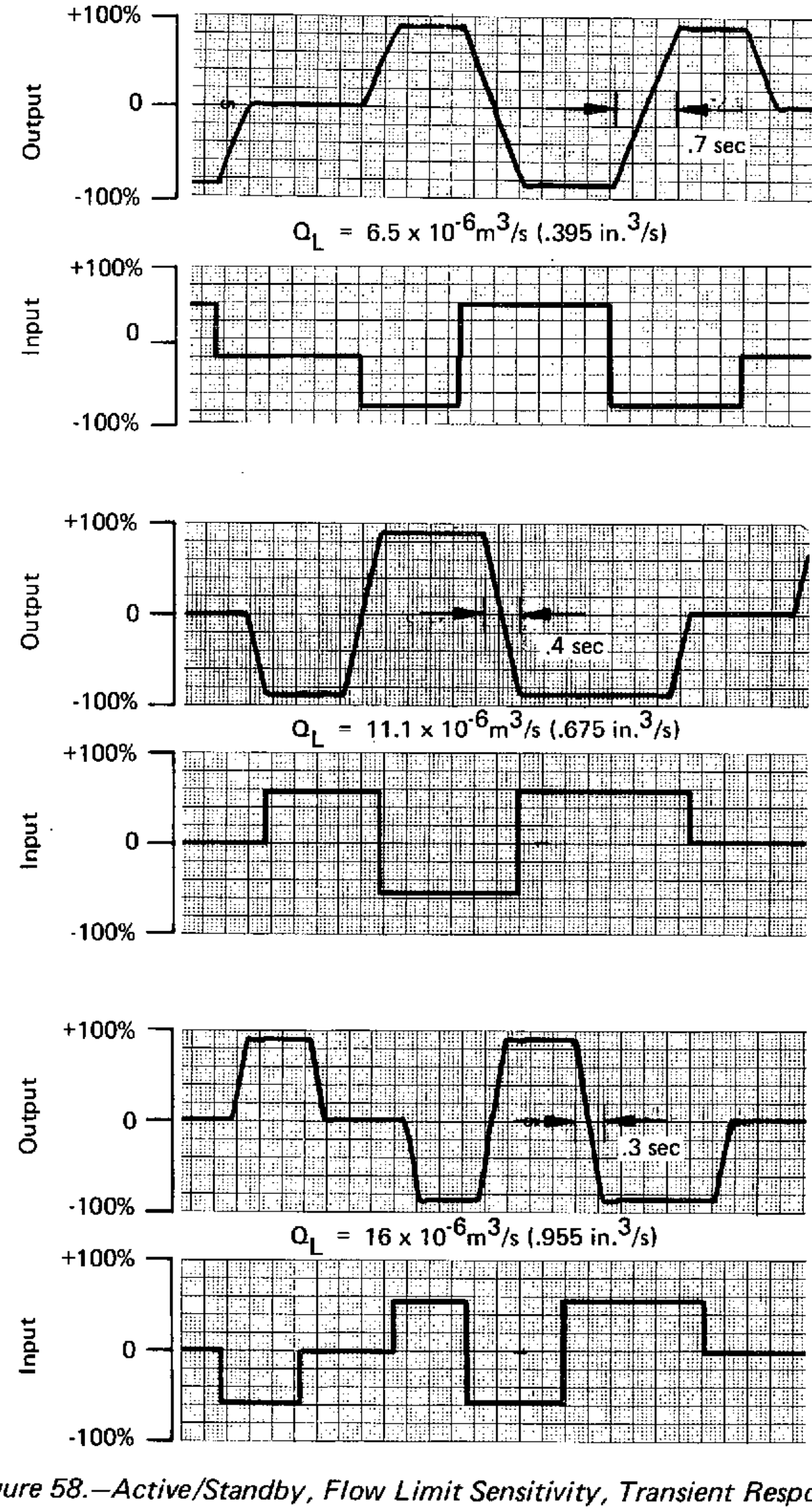


Figure 58.—Active/Standby, Flow Limit Sensitivity, Transient Response

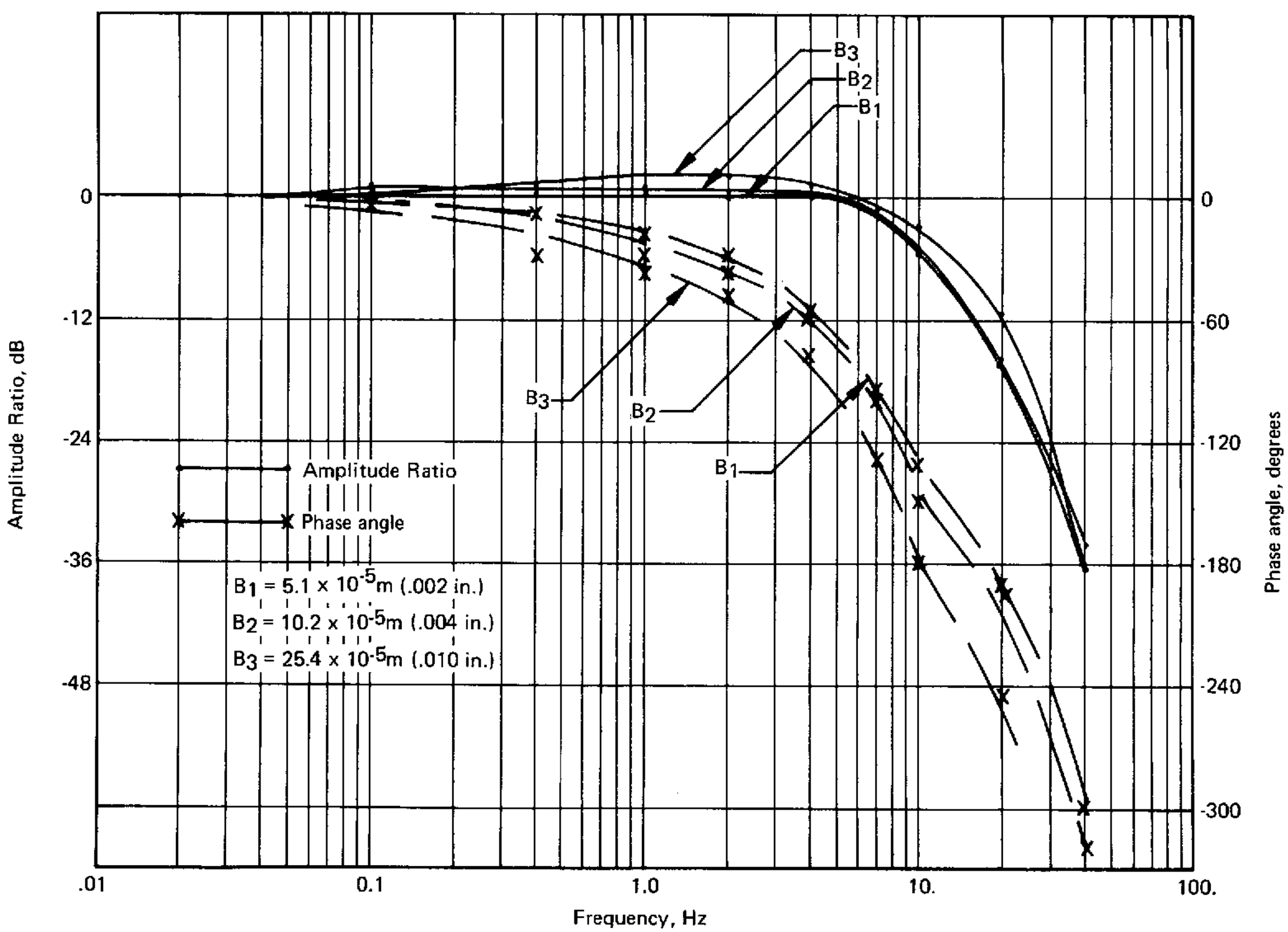


Figure 59.—Active/Standby, Backlash Sensitivity Frequency Response

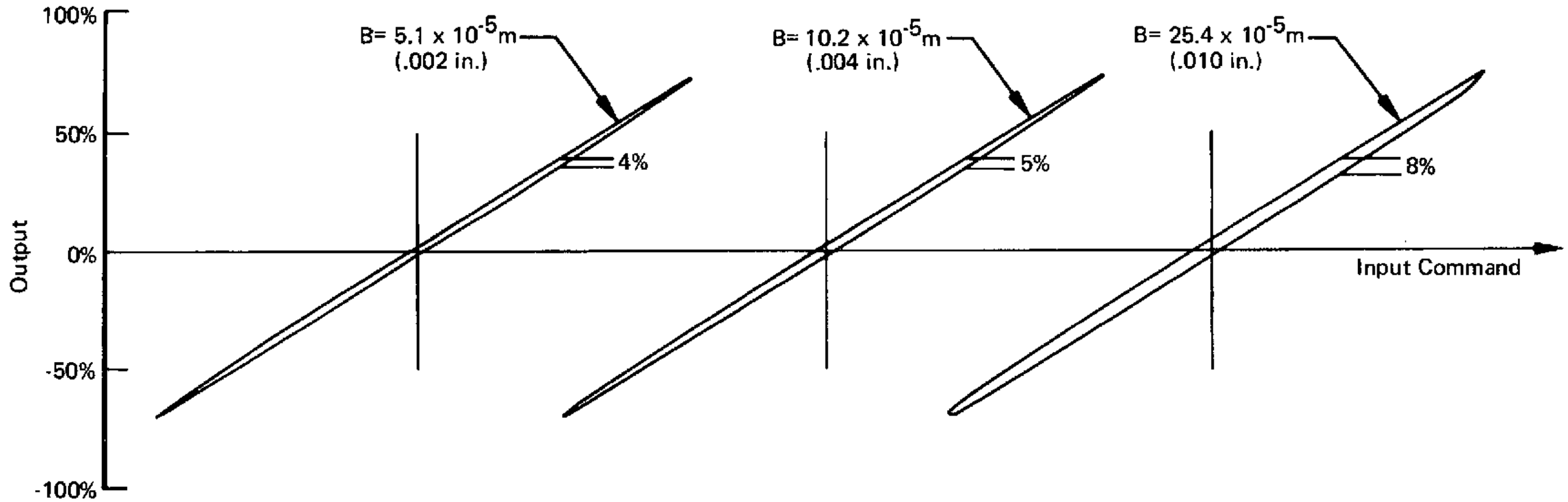


Figure 60.—Active/Standby, Backlash Sensitivity, Resolution

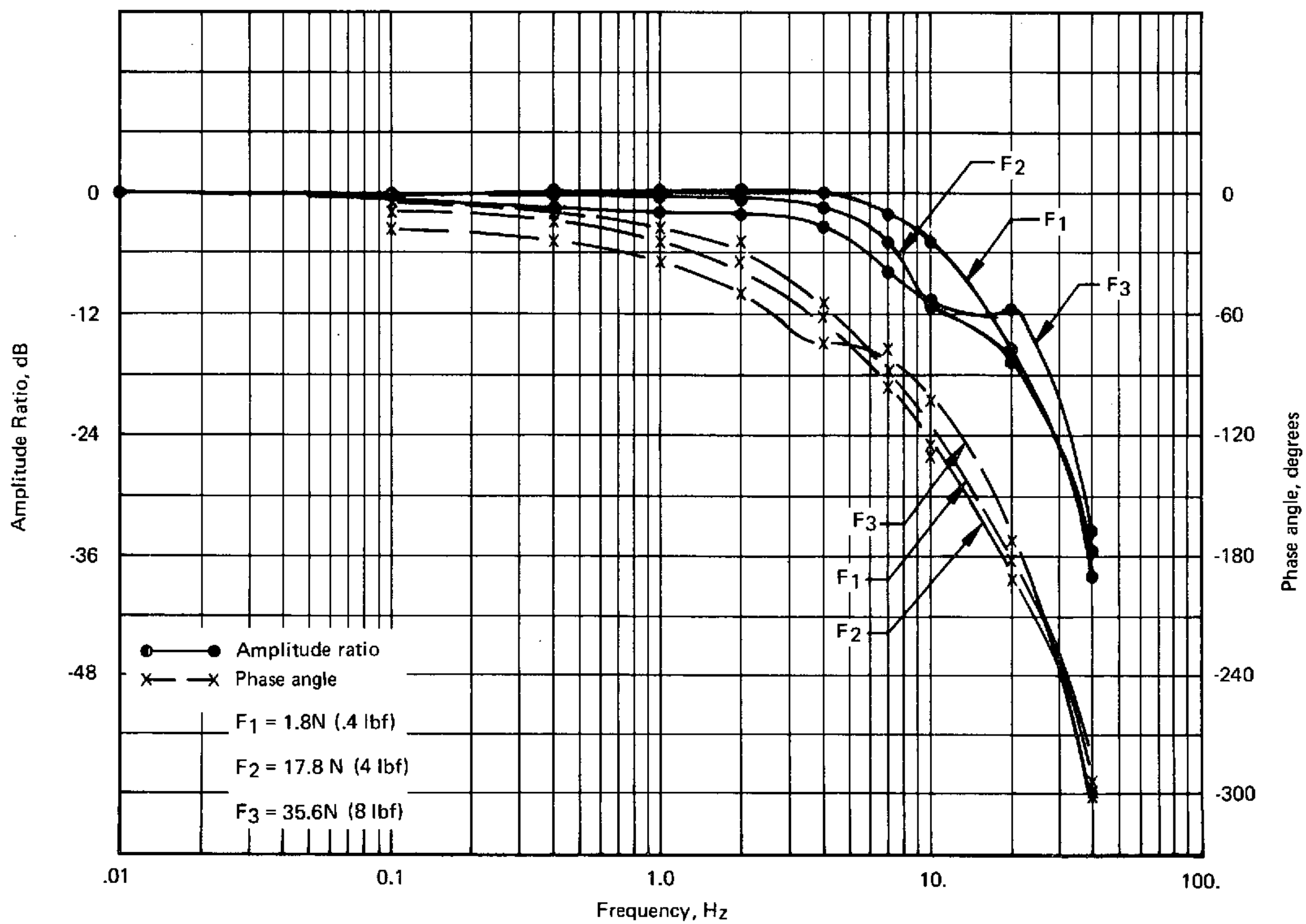


Figure 61.—Active/Standby Friction Sensitivity, Frequency Response

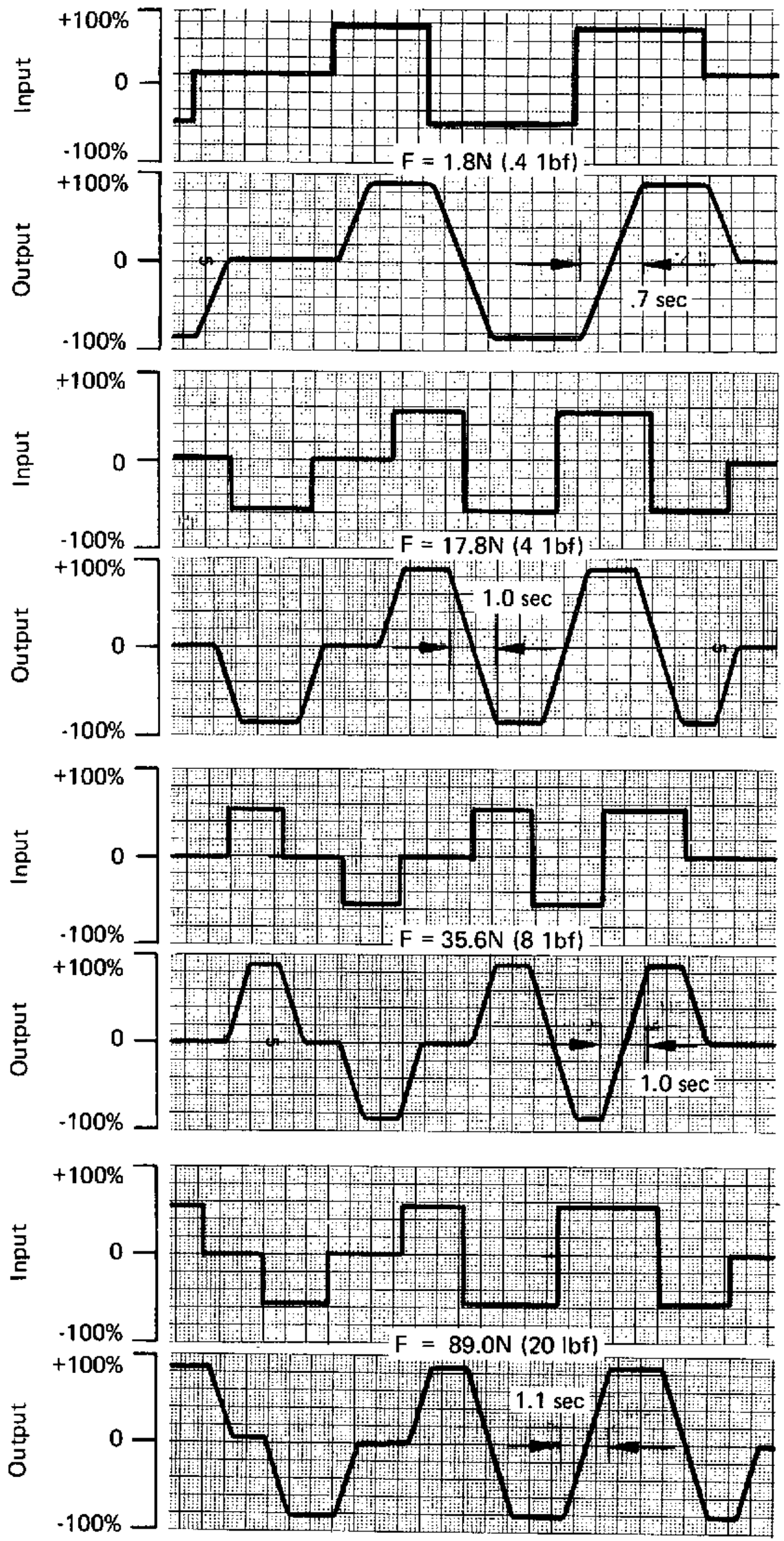


Figure 62.—Active/Standby Friction Sensitivity, Transient Response

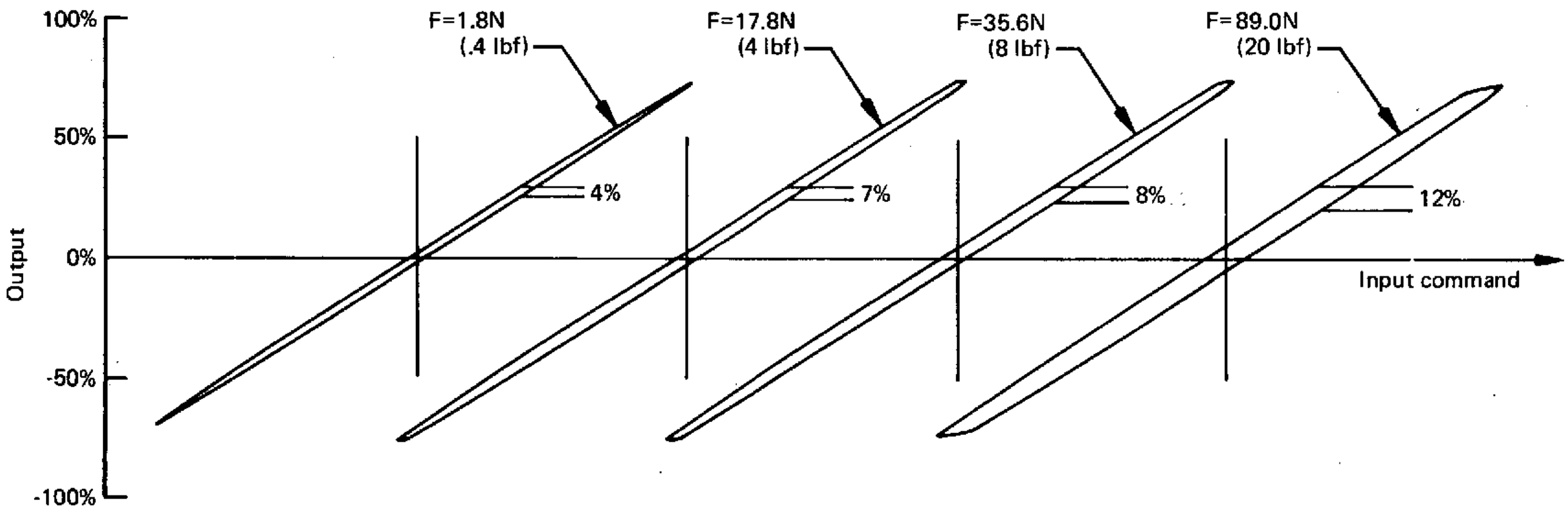


Figure 63.—Active/Standby Friction Sensitivity, Resolution

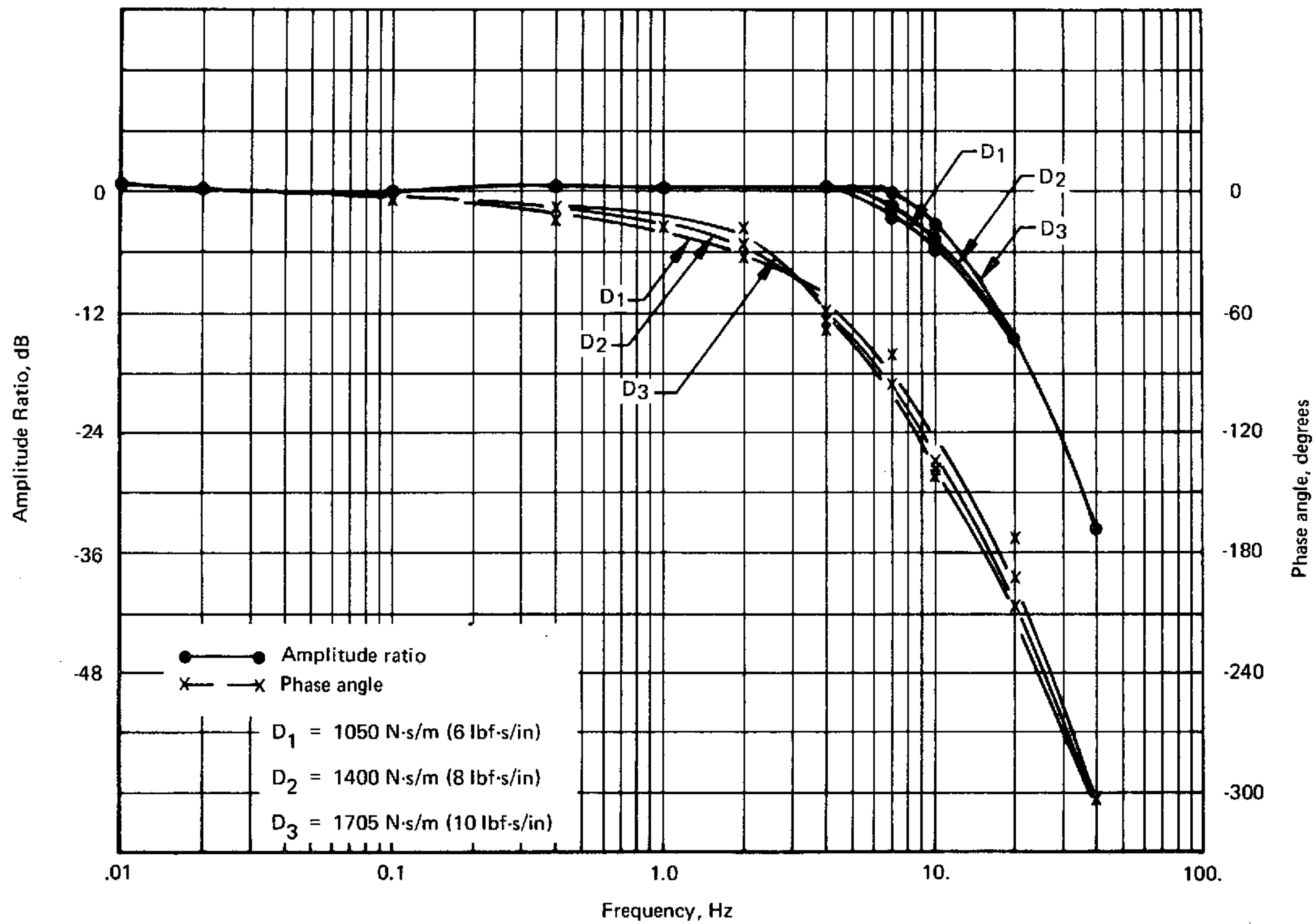


Figure 64.—Active/Standby Damping Sensitivity Frequency Response

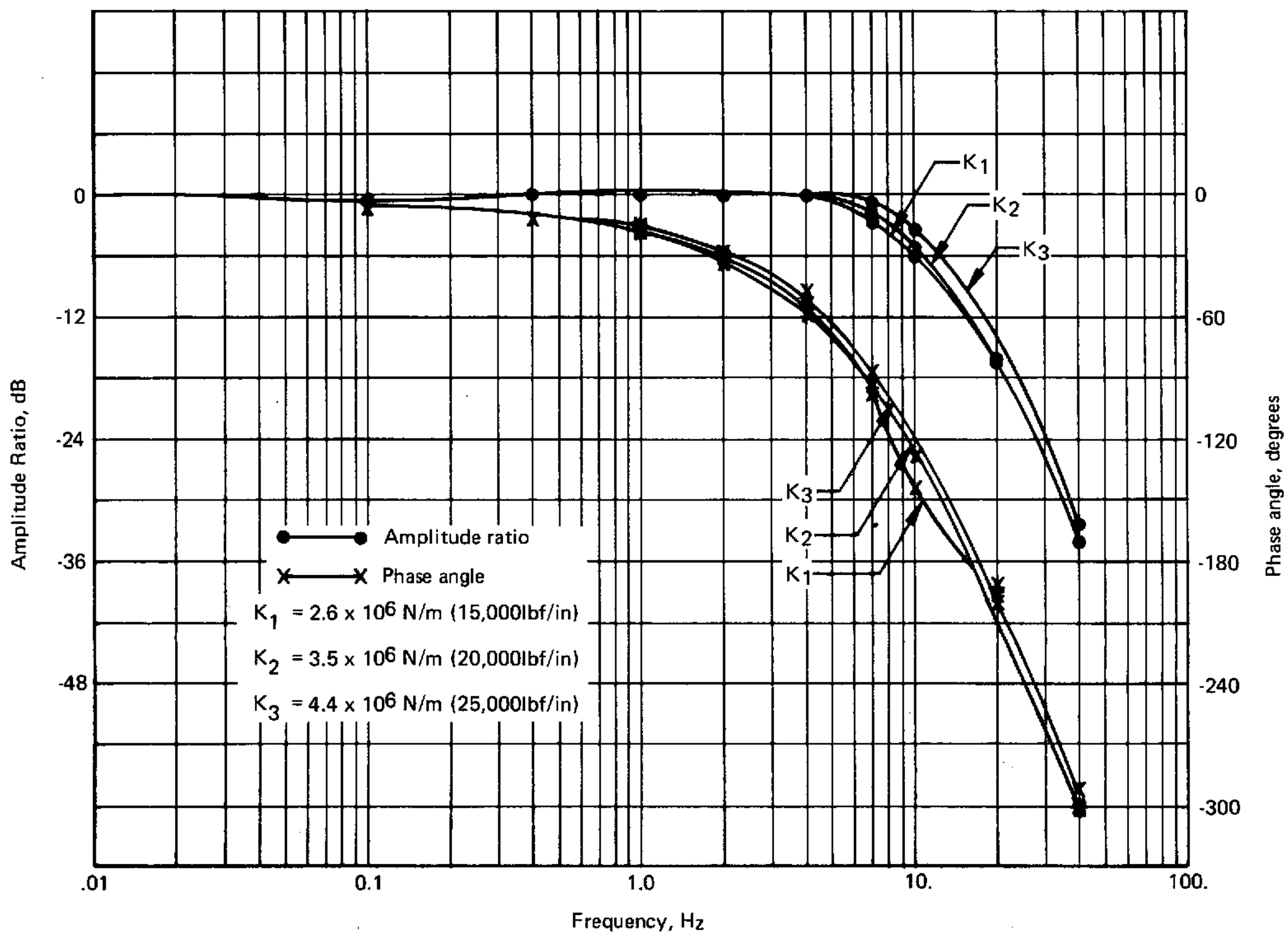


Figure 65.—Active/Standby, Rod Spring Sensitivity, Frequency Response

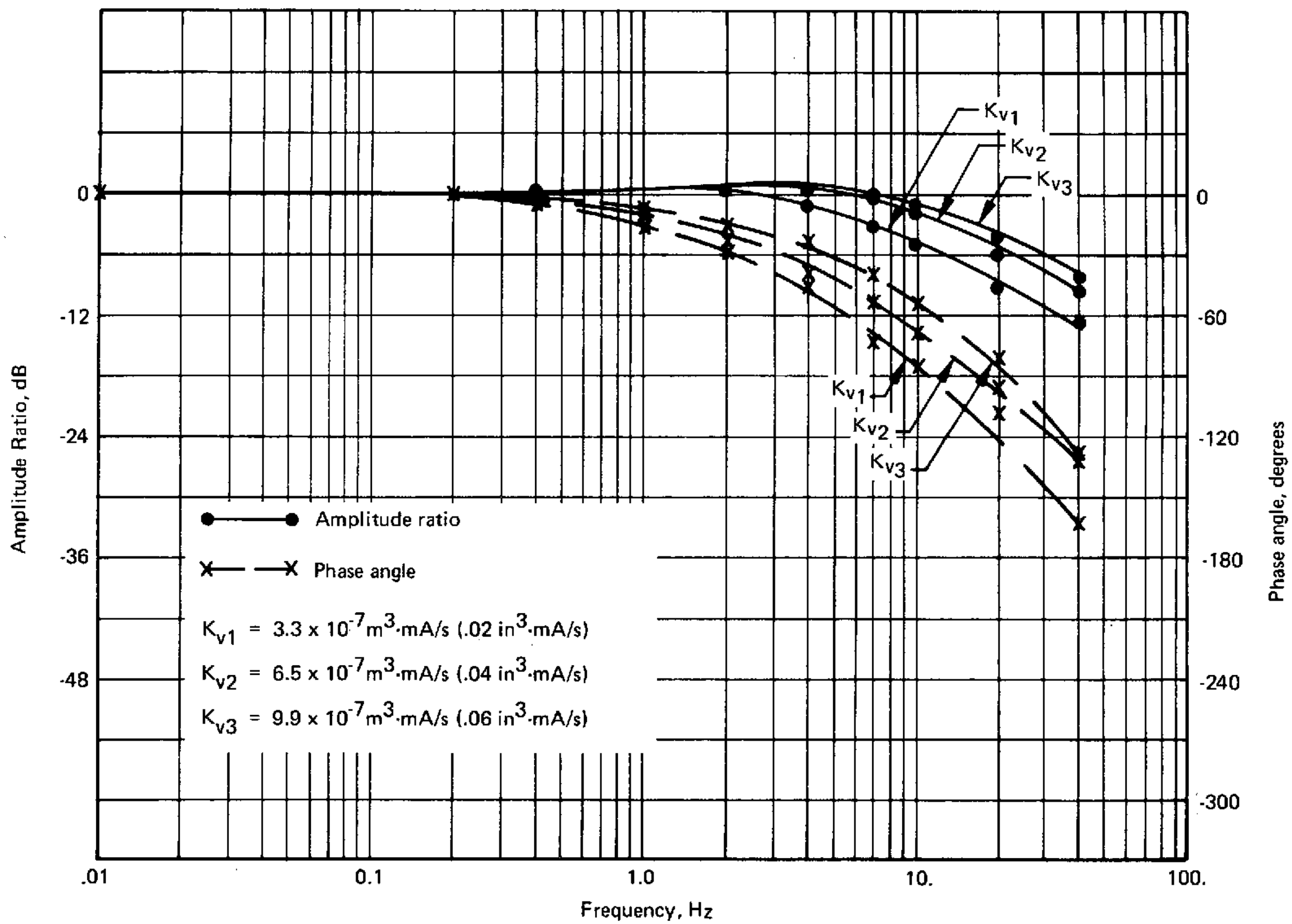


Figure 66.—Force Summed Flow Gain Sensitivity, Frequency Response

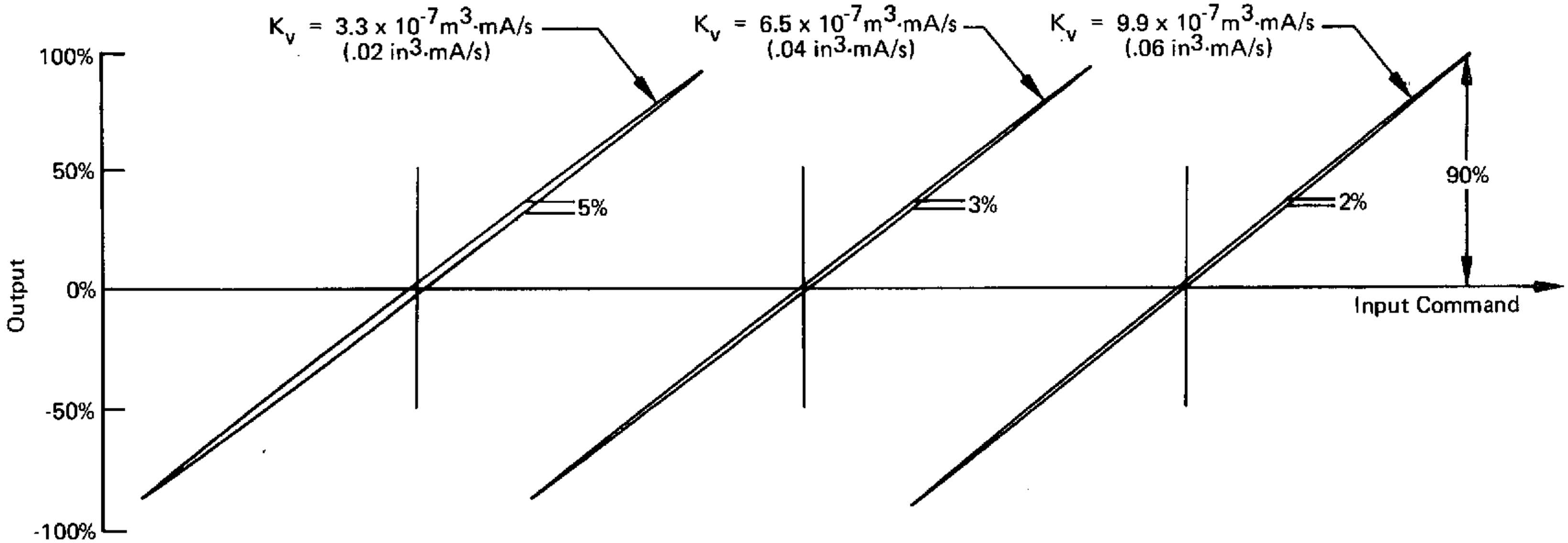


Figure 67.—Force Summed Flow Gain Sensitivity, Resolution

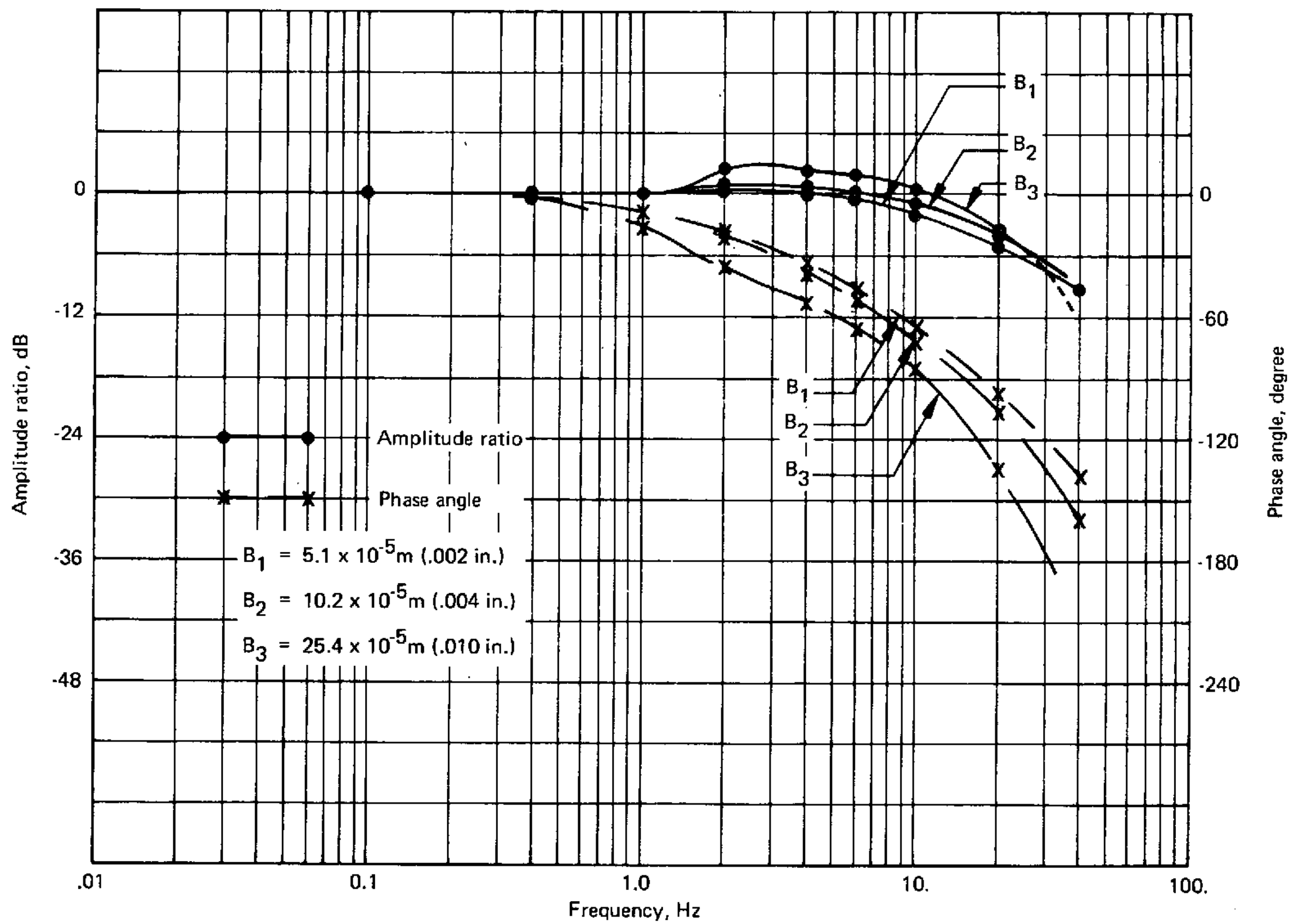


Figure 68.—Force-Summed Backlash Sensitivity, Frequency Response

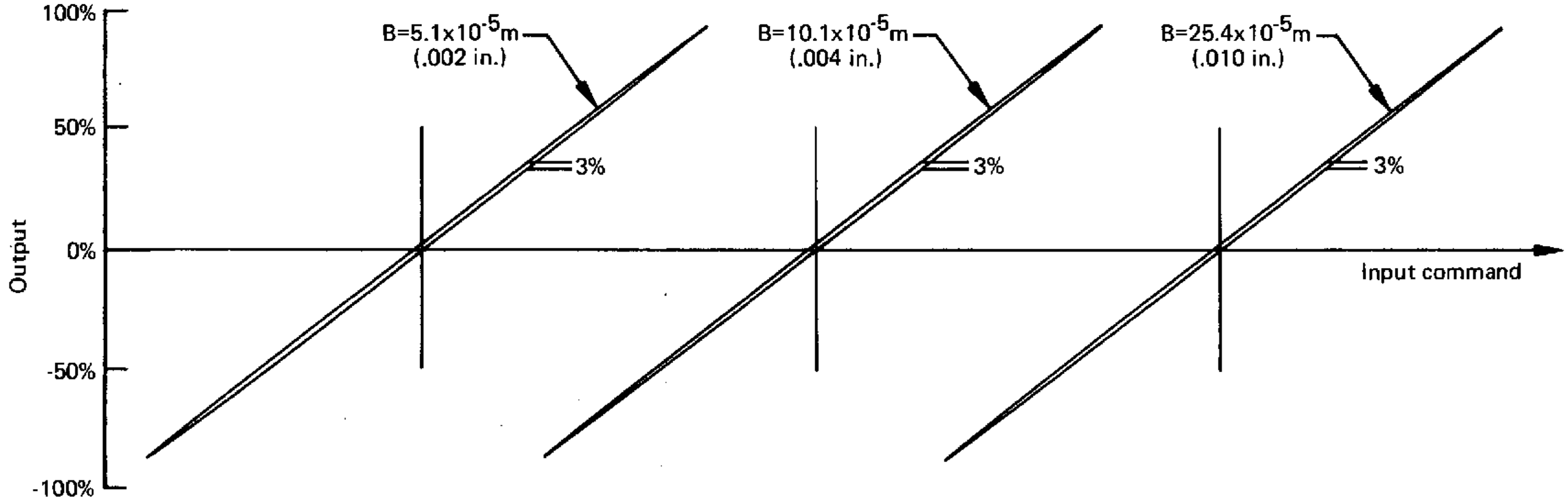


Figure 69.—Force Summed Backlash Sensitivity, Resolution

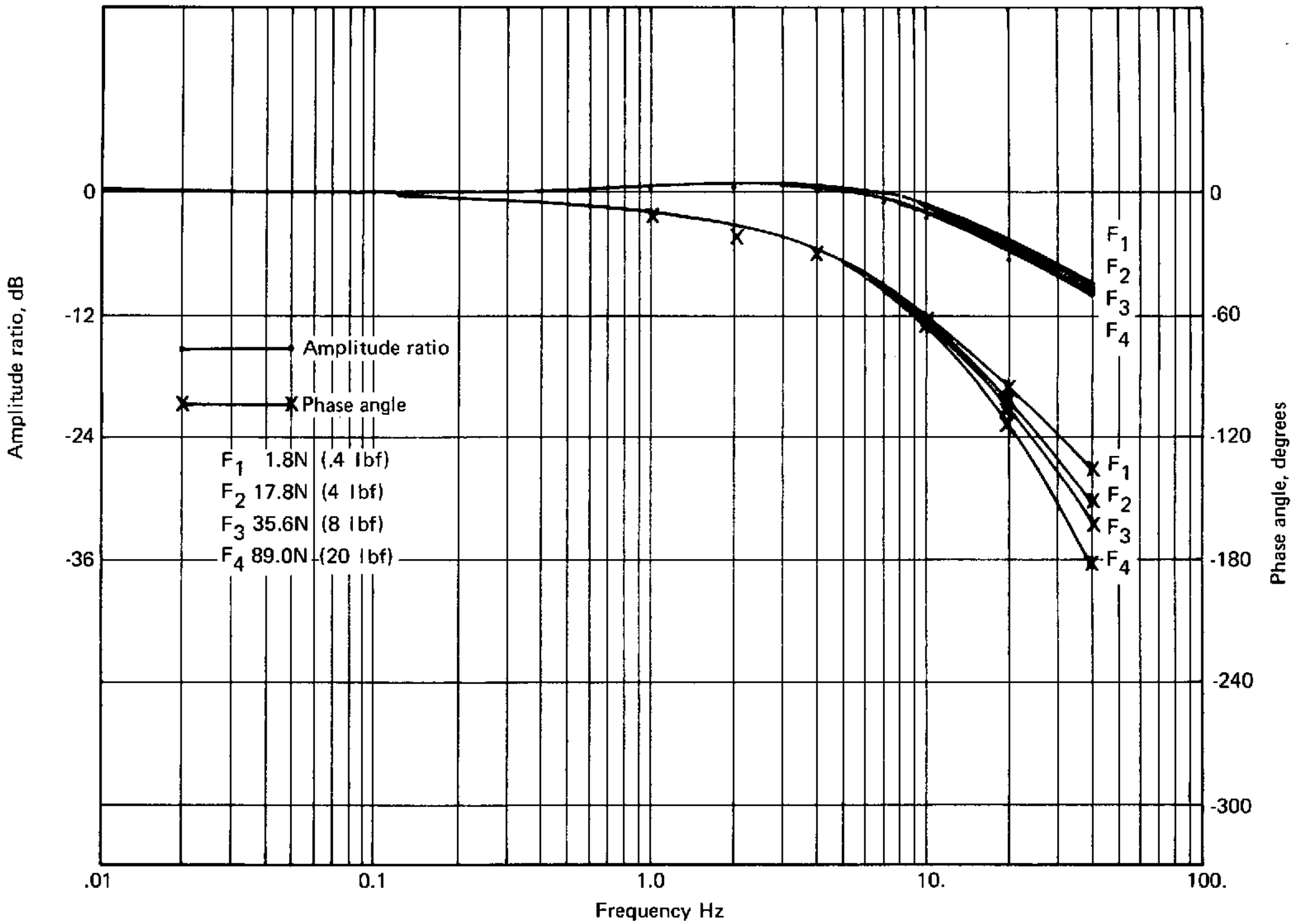


Figure 70.—Force-Summed Friction Sensitivity, Frequency Response

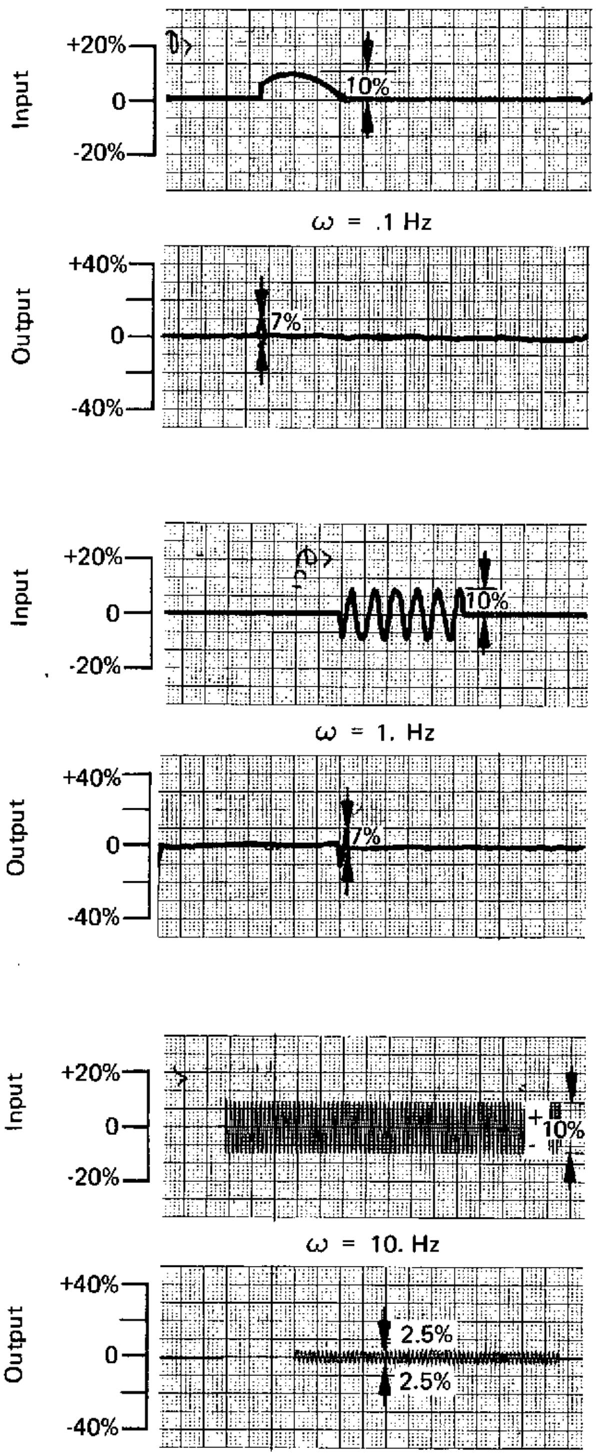


Figure 71.—Typical Active/Standby Failure Response, Oscillatory

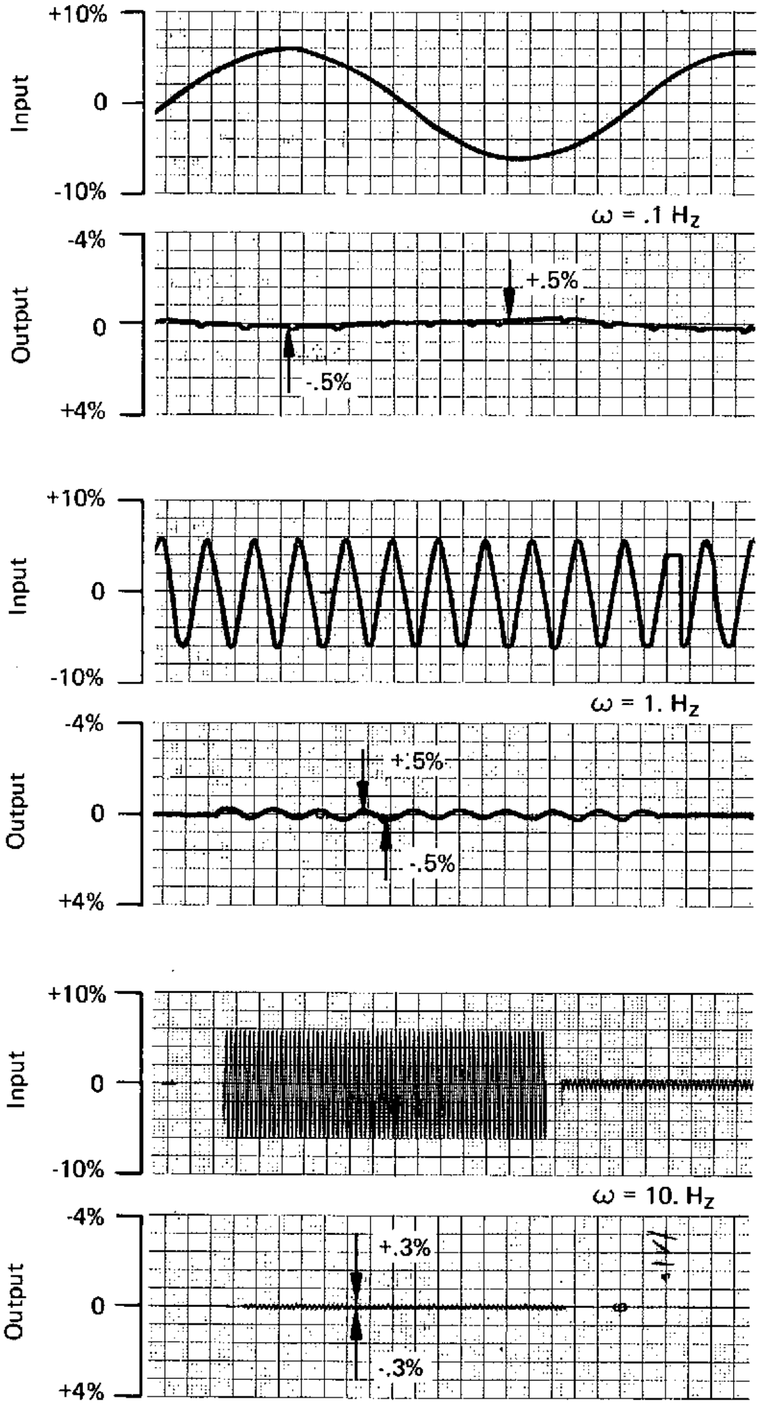


Figure 72.—Typical Force Summed Failure Response, Oscillatory

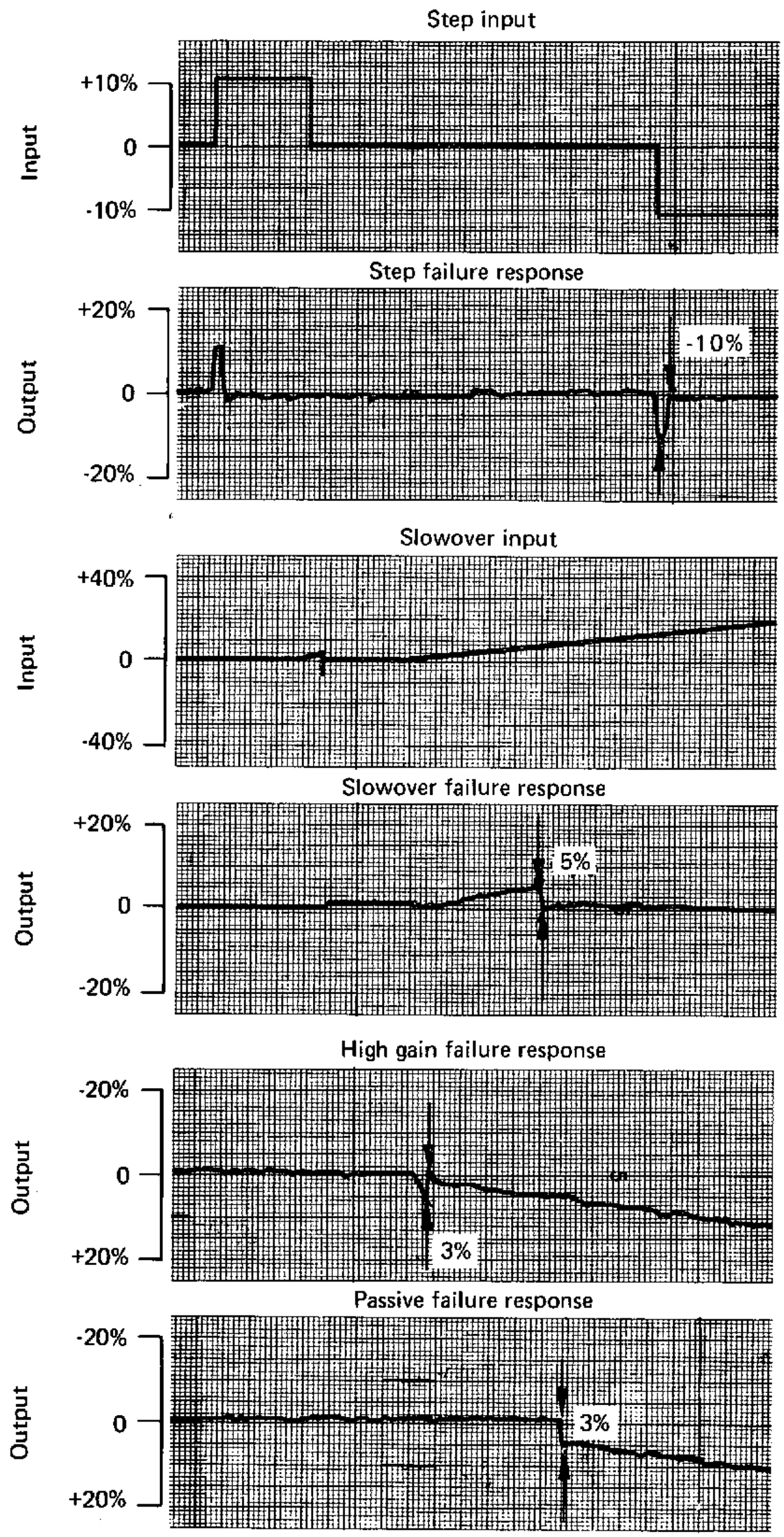


Figure 73.—Typical Active/Standby Failure Response, Step, Slowover, High Gain, and Passive

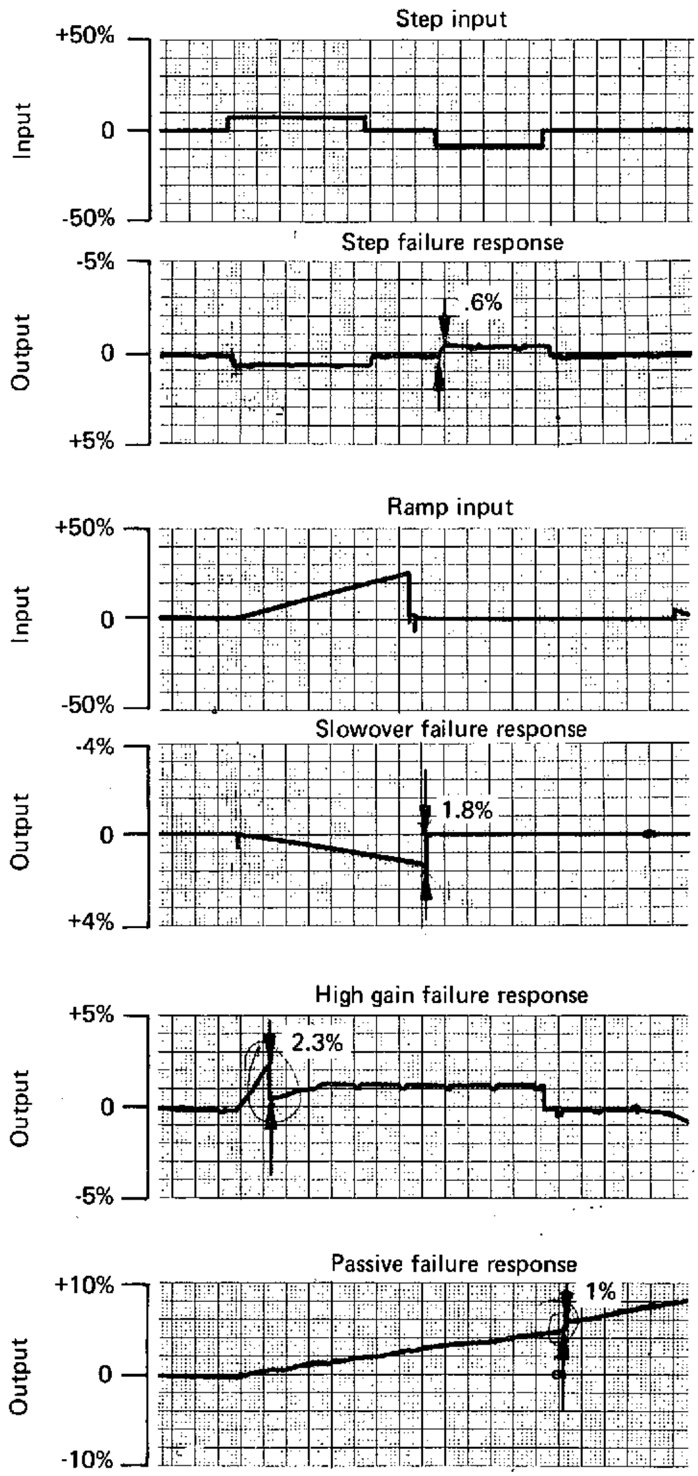


Figure 74.—Typical Force Summed Failure-Response, Step Slowover, High Gain and Passive

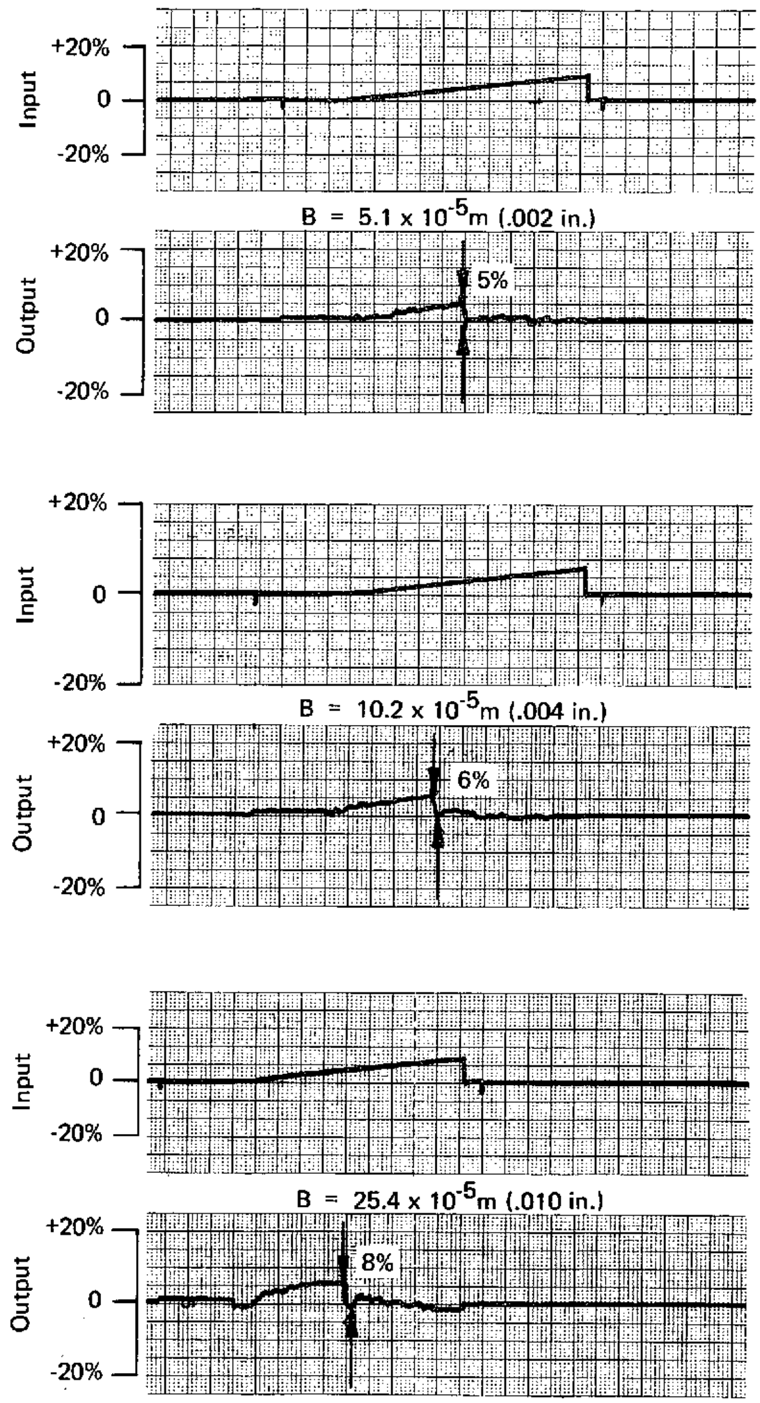


Figure 75.—Active/Standby Backlash Sensitivity, Failure Response

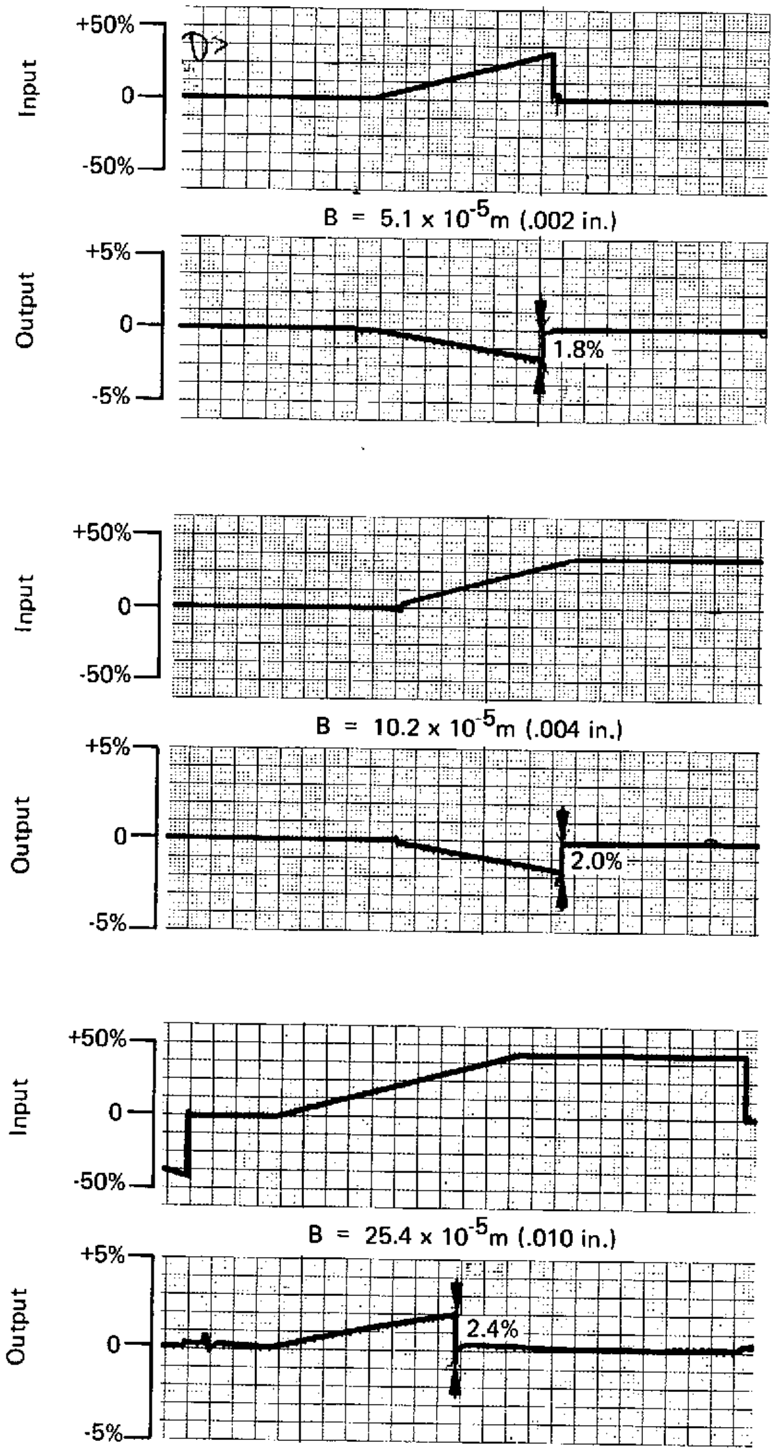


Figure 76.—Force Summed, Backlash Sensitivity, Failure Response

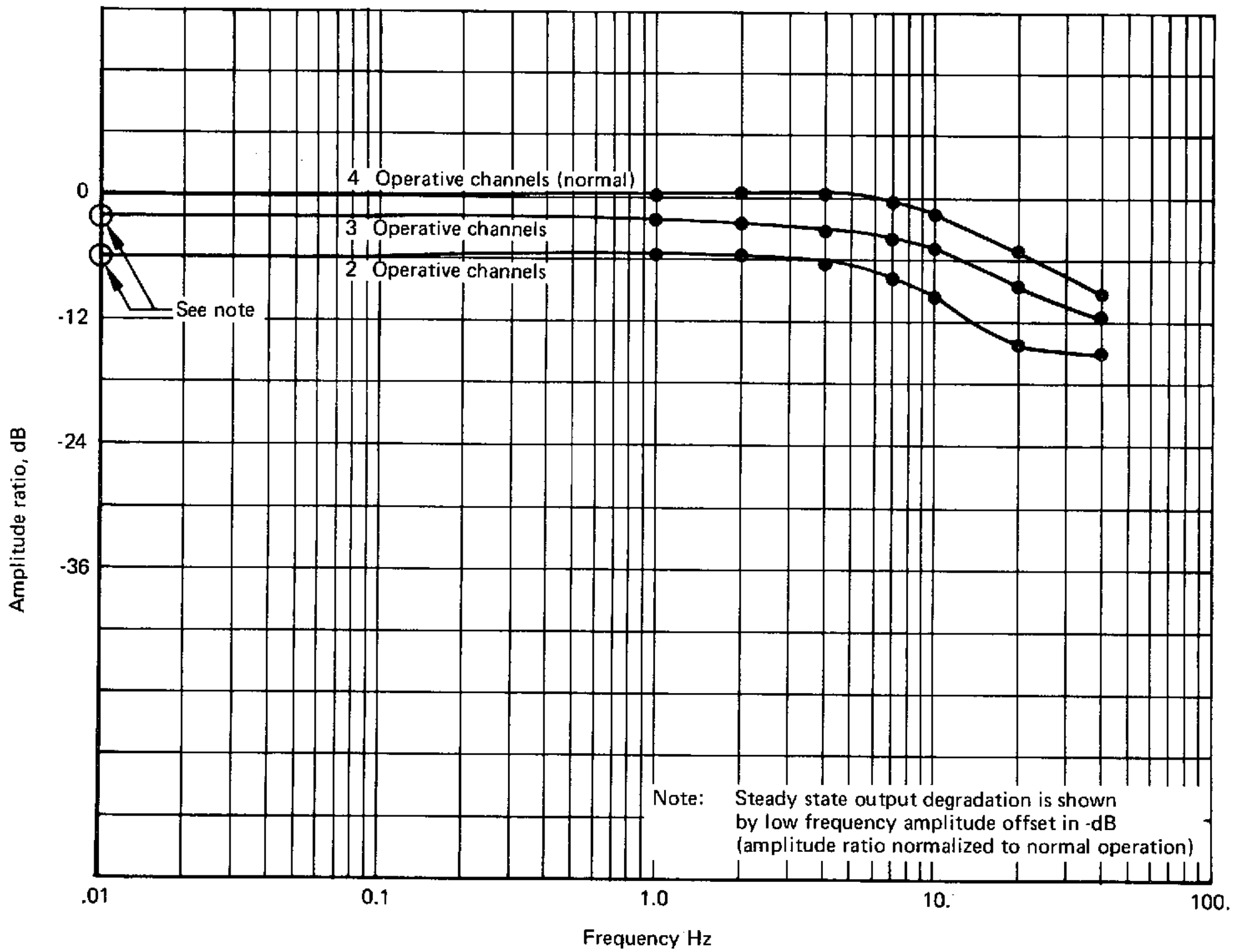


Figure 77.—Force-Summed Failed Channel Sensitivity, Frequency Response

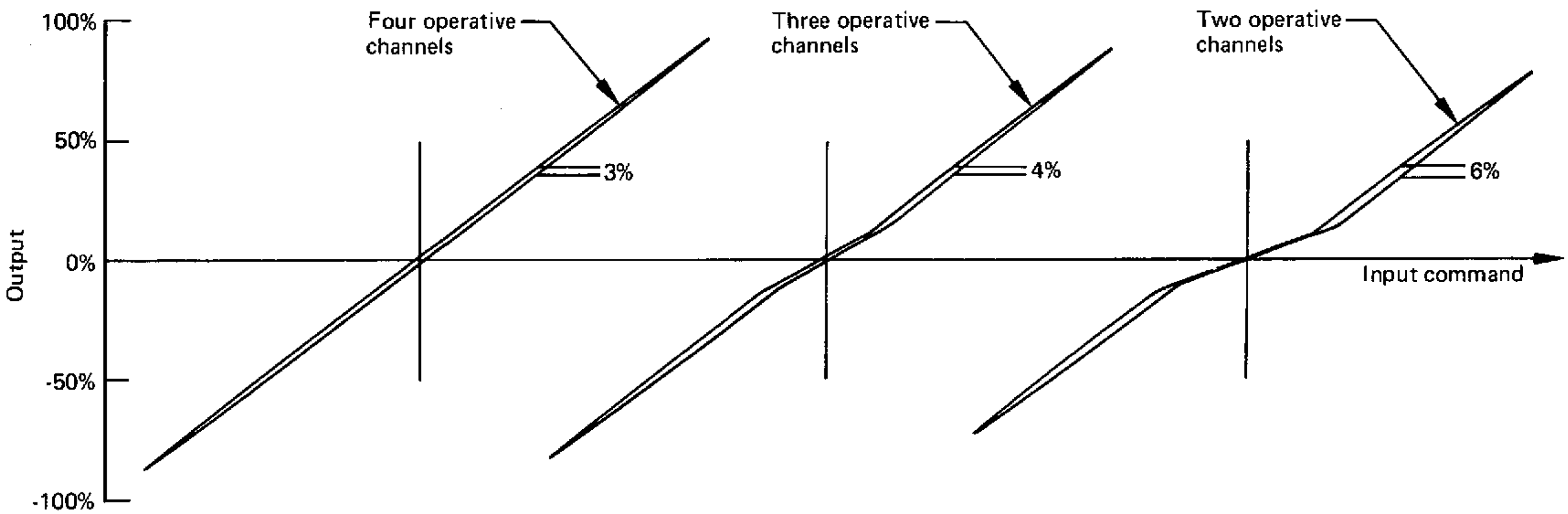
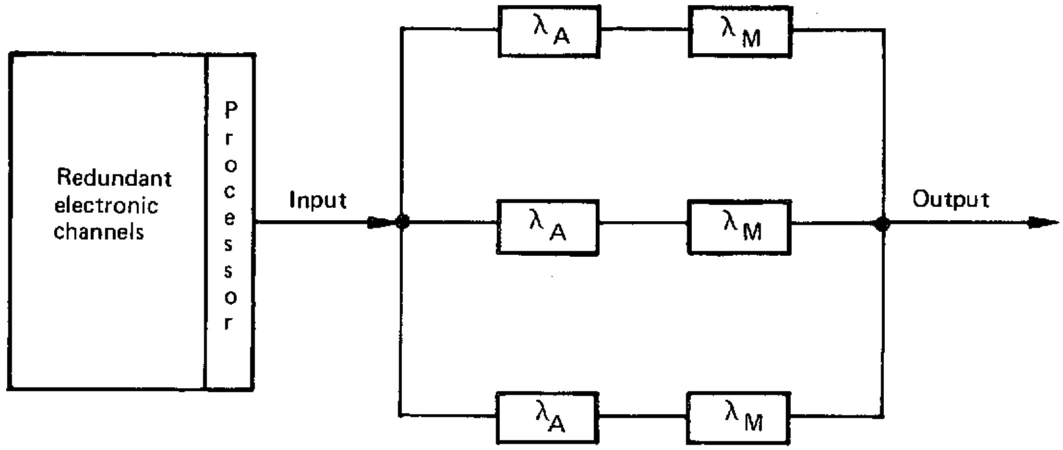
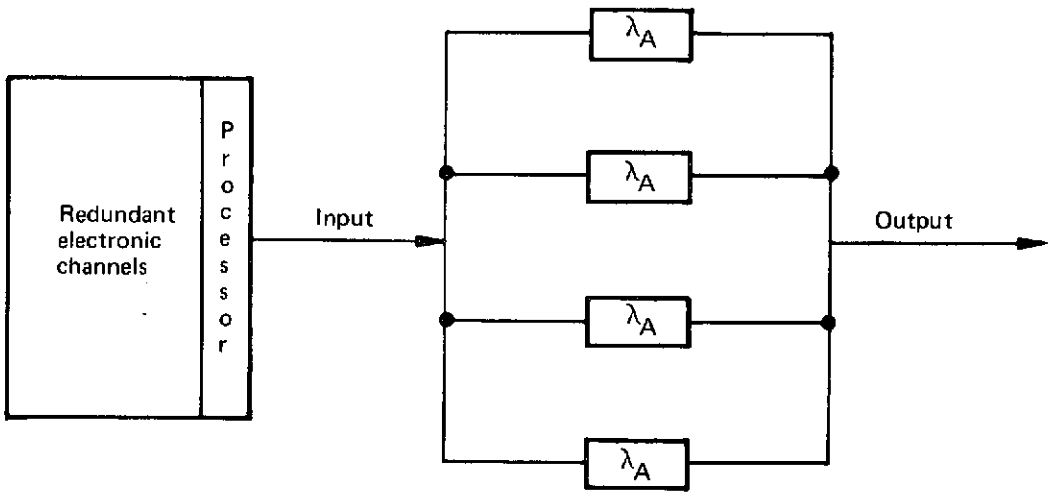


Figure 78.—Force Summed Failed Channel Sensitivity, Resolution



Active/Standby



Force Summed

λ_A = Failure rate of actuator channel

λ_M = Failure rate of monitor (model) channel

Figure 79.—Reliability Comparison-Success Diagrams

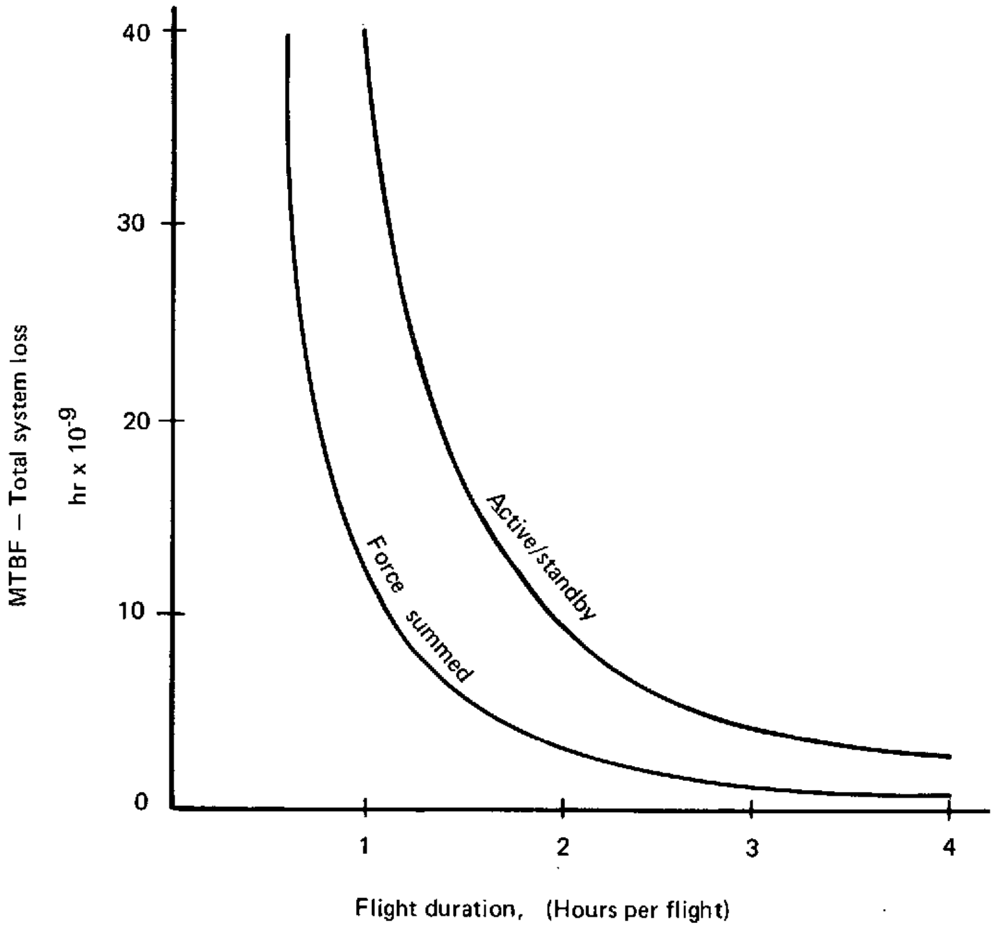


Figure 80.—Safety Reliability Comparison

Table 4.—Summary of FSAA Simulator Testing Procedure

Cruise and landing approach		
Failure category	Handling qualities level	
	Normal	Min. safe
Step	Introduce secondary actuator steps. Increase magnitude until airplane becomes unflyable.	
Slowovers	Introduce secondary actuator slowovers. Increase slowover rate until airplane becomes unflyable.	
Oscillations	Introduce secondary actuator oscillations. Vary frequency and amplitude. Map effect on handling qualities.	
Control discontinuity	Open command path through secondary actuator momentarily. Vary time increment and map effects on handling qualities.	

Cruise and landing approach		
Evaluation category	Handling qualities levels	
	Normal	Min. safe
Dead band	Vary secondary actuator dead band. Map effects on handling qualities.	
Hysteresis	Vary secondary actuator hysteresis. Map effects on handling qualities.	
Threshold	Vary secondary actuator threshold. Map effects on handling qualities.	

Table 5.—Summary of Active Standby Valve/Monitor Configuration Selection Tests

Failure category	Valve/monitor configurations		
	Configuration I	Configuration II	Configuration III
Slowover	Input .25 deg/sec ramp to active channel until failure occurs. Record system response.		
High gain	Set feedback gain to zero on active channel. Input .25 deg/sec ramp to this channel-record system response.		
Step	Shift input null of active channel 1%, 10% and 20% of maximum command – record system response.		
Command signal oscillation	Oscillatory input to active channel, peak amplitude at 1% and 10% of maximum command signal at frequencies of 0.1 Hz, 1.0 Hz and 10 Hz respectively.		

Table 6.—Summary of Force Summed Valve Configuration Selection Tests

Test category	Valve pressure gain (K_p) x 10^{-7} Pa/mA (psi/mA)					
	0.138 (200)	0.241 (350)	0.345 (500)	1.379 (2000)	6.895 (10000)	13.790 (20000)
Frequency response	Input sinusoidal command (5% of $e_{c_{max}}$ to system at the following frequencies: .05; .5; 2.5; 5.; 10.; 15.; 25.; 50. Hz . Measure amplitude ratio and phase shift between output and input at each frequency.					
Transient response	Input step command (90% of $e_{c_{max}}$). Measure time for system to transition to commanded position.					
Resolution	Input sinusoidal command to system (90% of $e_{c_{max}}$) at .01 Hz. Record output versus input signal and measure hysteresis and dead band.					

Rerun tests with valve pressure gains equal to .241 x 10^7 Pa/mA (350 psi/mA) and 6.895 x 10^7 Pa/mA (10000 psi/mA) and with one and two channels failed respectively.

Table 7.—Nominal Actuator Parameters

Symbol	Description	Value
K_{v1}	Servovalve first stage flow gain	1.47×10^{-6} m^3/sec (.09 in^3/s)
K_{p1}	Servovalve first stage pressure gain	1.52×10^6 Pa/mA (220 psi/mA)
K_{v2}	Servovalve second stage flow gain	6.57×10^{-7} m^3/s (.04 in^3/s)
K_{p2}	Servovalve second stage pressure gain	6.89×10^7 Pa/mA (1×10^4 psi/mA)
K	Actuator dynamic stiffness $\left(\frac{4A\beta Ks_1}{Ks_1 L + 4A\beta}\right)$	1.92×10^6 N/m (1.095×10^4 lbf/in)
A	Piston area	1.86×10^{-4} m^2 (.289 in^2)
D_p	Piston damping coefficient	1.4×10^3 N/m (8 lbf-s/in)
M_p	Piston mass	5.95 Kg (.034 lb-s^2/in)
F_f	Piston friction	1.78N (.4 lbf)
K_{s1}	Actuator backup structural stiffness	1.98×10^6 N/m (1.13×10^4 lbf/in)
K_{s2}	Actuator rod stiffness	1.75×10^{11} N/m (1×10^9 lbf/in)
M_L	Load mass	56 Kg (.32 lb-s^2/in)
D_L	Load damping	2.8×10^3 N-s/m (16 lbf-s/in)
K_a	Servo amplifier gain	28.27 mA/V
K_f	Position feedback gain $\left(K_F K_{d_m} K_x\right)$	6.12×10^2 V/m (15.54 V/in)
K_F	Amplifier gain	.89 V/V
K_{dm}	Demodulator gain	1.25 V/V
K_x	LVDT gain	5.5×10^2 V/m (14 V/in)
β	Oil bulk modulus	1.03×10^9 N/m^2 (1.5×10^5 lb/in^2)
L	Actuator stroke	$\pm 1.27 \times 10^{-2}$ m ($\pm$.5 in)

Table 8.—Frequency Response, Transient Response, and Resolution Test Procedure

Test	Procedure
Frequency response test	Input a .01 Hz, ±5% sinusoidal command signal into the test configuration. Then measure the position output and the command signal with a storage oscilloscope. Vary the command signal frequency and repeat the test procedure. System parameters are varied as per table 9 or table 11 for the active/standby or force summed systems, respectively.
Transient response test	Input a ±90% step command signal into the test configuration. Record the input command and the position output on a strip recorder. Vary system parameters as per table 9 or 11 for the active/standby or force summed systems, respectively.
Resolution test	Input a .01 Hz, ±90% sinusoidal command signal into the test configuration. Record the input command and the position output on an X-Y recorder. Vary system parameters as per tables 9 and 11, for the active/standby or force summed systems, respectively.

Table 9.—Parameter Values Used for Parameter Sensitivity Analysis, Active/Standby

Parameter			Parameter values			
Name	Symbol	Units	Nominal	First variation	Second variation	Third variation
Pressure gain	K_p	(psi/mA) Pa/mA	(10.0×10^3) 6.9×10^7	(2.0×10^3) 1.38×10^7	(20.0×10^3) 13.8×10^7	– –
Flow gain	K_v	$(in^3 \cdot mA/s)$ $m^3 \cdot mA/s$	(4.0×10^{-2}) 6.5×10^{-7}	(2.0×10^{-2}) 3.3×10^{-7}	(6.0×10^{-2}) 9.9×10^{-7}	– –
Flow limit	Q_L	(in^3/s) m^3/s	(3.95×10^{-1}) 6.5×10^{-6}	(6.75×10^{-1}) 11.1×10^{-6}	(9.55×10^{-1}) 16.0×10^{-6}	– –
Backlash	B	(in) m	(2.0×10^{-3}) 5.1×10^{-5}	(4.0×10^{-3}) 10.2×10^{-5}	(1.0×10^{-2}) 25.4×10^{-5}	– –
Friction	F	(lbf) N	(0.4) 1.8	(4.0) 17.8	(8.0) 35.6	(20.0) 89.0
Damping	D	(lbf·s/in) N·s/m	(8.0) 1.4×10^3	(6.0) 1.05×10^3	(10.0) 1.705×10^3	– –
Rod spring	K_s	(lbf/in) N/m	(2.0×10^4) 3.5×10^6	(1.5×10^4) 2.6×10^6	(2.5×10^4) 4.4×10^6	– –
Dynamic spring	K	(lbf/in) N/m	(11.0×10^3) 1.9×10^6	(8.5×10^3) 1.5×10^6	(13.5×10^3) 2.4×10^6	– –

Table 10.—Performance Sensitivity to Parameter Variation, Active/Standby[1]

Test Category	Test Parameter							
	K_p	K_v	Q_L	B	[2] F	D	K_s	K
Frequency response (-3 dB cutoff, Hz)	8.5 8.0 8.0	5.5 8.5 10.5	8.5 8.0 8.0	8.5 9.0 10.5	8.5 5.5 3.5	10.0 8.5 7.5	7.5 8.5 9.5	8.5 8.5 8.5
Frequency response (45° cutoff, Hz)	3.5 3.2 3.2	2.5 3.5 4.0	3.5 3.5 3.5	3.5 2.5 1.7	3.5 2.3 1.5	3.5 3.5 3.5	3.0 3.5 4.0	3.0 3.5 3.5
Transient response (transition time, sec)	0.7 0.7 0.7	0.7 0.7 0.7	0.7 0.4 0.3	– – –	0.7 1.0 1.0 1.1	0.7 0.7 0.7	– – –	0.7 0.7 0.7
Resolution (hysteresis loss, % of X_{max})	4.0 4.0 4.0	6.0 4.0 4.0	– – –	4.0 5.0 8.0	4.0 7.0 8.0 12.0	– – –	– – –	4.0 4.0 4.0
Slow Over (failure transient, % of X_{max})	5.0 5.0 5.0	5.0 5.0 5.0	5.0 5.0 5.0	5.0 6.0 8.0	[3]5.0 5.0 4.5	5.0 5.0 5.0	– – –	– – –

(1) The top entry in each box corresponds to the smaller parameter value, the bottom entry to the largest parameter value.

(2) The 20 lbf friction data for frequency response was very noisy and was not used for evaluation.

(3) The tested friction values for the slow over tests were 1.8N, 3.6N, and 8.9N (0.4 lbf, 0.8 lbf, and 2.0 lbf).

Table 11.—Parameter Values Used for Parameter Sensitivity Analysis, Force Summed

Parameter			Parameter values			
Name	Symbol	Units	Nominal	First variation	Second variation	Third variation
Pressure gain	K_p	(psi/mA) Pa/mA	(2.2×10^2) 1.5×10^6	(3.5×10^2) 2.4×10^6	(5.0×10^2) 3.4×10^6	–
Flow gain	K_v	$(in^3 \cdot mA/s)$ $m^3 \cdot mA/s$	(4.0×10^{-2}) 6.5×10^{-7}	(2.0×10^{-2}) 3.3×10^{-7}	(6.0×10^{-2}) 9.9×10^{-7}	–
Flow limit	Q_L	(in^3/s) m^3/s	(3.95×10^{-1}) 6.5×10^{-6}	(6.75×10^{-1}) 11.1×10^{-6}	(9.55×10^{-1}) 16.0×10^{-6}	–
Backlash	B	(in) m	(2.0×10^{-3}) 5.1×10^{-5}	(4.0×10^{-3}) 10.2×10^{-5}	(1.0×10^{-2}) 25.4×10^{-5}	–
Friction	F	(lbf) N	(0.4) 1.8	(4.0) 17.8	(8.0) 35.6	(20.0) 89.0
Damping	D	(lbf·s/in) N·s/m	(8.0) 1.4×10^3	(6.0) 1.05×10^3	(10.0) 1.705×10^3	–
Rod spring	K_s	(lbf/in) N/m	(2.0×10^4) 3.5×10^6	(1.5×10^4) 2.6×10^6	(2.5×10^4) 4.4×10^6	– –
Dynamic spring	K	(lbf/in) N/m	(11.0×10^3) 1.9×10^6	(8.5×10^3) 1.5×10^6	(13.5×10^3) 2.4×10^6	–

Table 12.—*Performance Sensitivity to Parameter Variation, Force Summed*[1]

Test Category	Test Parameters K_p	K_v	Q_L	B	F	D	K_s	K
Frequency response (-3 dB cutoff, Hz)	14.0 13.5 13.5	7.5 13.5 18.0	13.5 14.0 13.5	13.5 15.5 20.0	13.5 13.5 13.5 12.0	13.0 13.5 13.5	13.0 13.5 13.0	14.0 13.5 13.5
Frequency response (45^o cutoff, Hz)	6.5 6.0 7.0	4.0 6.0 8.0	6.0 6.5 6.0	6.0 5.5 3.0	6.0 6.0 6.0 7.5	7.0 6.0 6.5	5.5 6.0 7.0	6.0 6.0 6.5
Transient response (transition time—sec)	0.7 0.7 0.7	0.8 0.7 0.7	0.7 0.4 0.3	– – –	0.7 0.7 0.7 0.7	0.7 0.7 0.7	– – –	0.7 0.7 0.7
Resolution (hysteresis loss, % of X_{max})	3.0 3.0 3.0	5.0 3.0 2.0	– – –	3.0 3.0 3.0	3.0 3.0 3.0 3.0	– – –	– – –	3.0 3.0 3.0
Slowover (failure transient, % of X_{max})	1.8 1.8 1.8	1.8 1.8 1.8	1.8 1.8 1.8	1.8 2.0 2.4	1.8 1.6 1.6 1.6	1.8 1.8 1.8	– – –	1.8 1.8 1.8

(1) The top entry in each box corresponds to the smallest of the parameter values, the bottom entry to the largest parameter value.

Table 13.—Slowover-Induced Failure Transients, Active/Standby

	Failure Transient, % of X_{max}					
	K_p	K_v	Q_L	B	$^{(1)}F$	D
Nominal parameter	5	5	5	5	5	5
1st deviation	5	5	5	6	5	5
2nd deviation	5	5	5	8	4.5	5
3rd deviation	–	–	–	–	5	–

(1) Friction values for the slowover tests were 1.8N, 3.6N, and 8.9N (0.4 lbf, .8 lbf, and 2.0 lbf).

Table 14.—Slowover-Induced Failure Transients, with Position Offsets, Active/Standby

	Failure Transient(1)		
Position offset % of X_{max}	Offset the active actuator (% of X_{max})	Offset the active monitor (% of X_{max})	Offset the standby actuator (% of X_{max})
0	5	5	5
1.25	5	6, 3	6, 3
2.5	5	7, 2	8, 2

(1) Whenever two failure transient values are given, the larger value represents the failure transient for the actuator driving away from the position offset, and the smaller value is for the actuator driving in the direction of the position offset.

Table 15.—Oscillatory-Induced Failure Transients, Active/Standby

Failure conditions			Failure response	
Oscillatory		Standby channel offset (% of X_{max})	Failure transient (% of X_{max})	Failure detected (Yes, No)
Freq (Hz)	Amp (% of X_{max})			
0.1	10.0	0.0	7.0	Yes (1)
1.0	10.0	0.0	7.0	Yes (1)
10.0	10.0	0.0	±2.5	No
0.1	10.0	1.25	8.0	Yes (1)
1.0	10.0	1.25	10.0	Yes (1)
10.0	10.0	1.25	±2.5	No
0.1	10.0	2.50	12.0	Yes (1)
1.0	10.0	2.50	12.0	Yes (1)
10.0	10.0	2.50	±2.5	No
0.1	1.0	2.50	±1	No
1.0	1.0	2.50	±1	No
10.0	1.0	2.50	±.5	No

(1) Low-frequency, large amplitude oscillations are detected as a slow-over failure.

Table 16.—Step-Induced Failure Transients, Active/Standby

Step (% of X_{max})	Standby channel offset (% of X_{max})	Failure transient (% of X_{max})
1	0.0	1.5
10	0.0	10
1	1.25	1.5
10	1.25	11
1	2.5	1
10	2.5	14

Table 17.—High-Gain and Passive Induced Failure Transients, Active/Standby

Failure category	Standby channel offset (% of X_{max})	Failure transient (% of X_{max})
High gain	0.0	3
High gain	1.25	7
High gain	2.5	10
Passive	0.0	3
Passive	1.25	6
Passive	2.5	8

Table 18.—Slowover-Induced Transients, Force Summed

	Failure Transient, % of X_{max}							
	K_p	K_v	Q_L	B	F	D	K	ΔV
Nominal parameter	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
1st deviation	1.8	1.8	1.8	2.0	1.6	1.8	1.8	1.8
2nd deviation	1.8	1.8	1.8	2.4	1.6	1.8	1.8	1.8
3rd deviation	–	–	–	–	1.6	–	–	–

Table 19.—Oscillatory Failure Induced Transients, Force Summed

Failure conditions				Failure response	
Oscillatory		Position offset	Disengaged channels	Output transients	Failure detected
Freq (Hz)	Amp (% of X_{max})	(% of X_{max})	(No.)	(% of X_{max})	(Yes, No)
0.1	10.0	0.0	0	.5	none
1.0	10.0	0.0	0	.5	
10.0	10.0	0.0	0	.3	
0.1	1.0	0.0	0	0.0	
1.0	1.0	0.0	0	0.0	
10.0	1.0	0.0	0	.15	
0.1	10.0	1.25	0	.5	
1.0	10.0	1.25	0	.5	
10.0	10.0	1.25	0	.3	
0.1	1.0	1.25	0	0.0	
1.0	1.0	1.25	0	0.0	
10.0	1.0	1.25	0	.15	
0.1	10.0	2.50	0	.5	
1.0	10.0	2.50	0	.5	
10.0	10.0	2.50	0	.3	
0.1	1.0	2.50	0	0.0	
1.0	1.0	2.50	0	0.0	
10.0	1.0	2.50	0	.15	
0.1	10.0	0.0	1	.5	
1.0	10.0	0.0	1	.5	
10.0	10.0	0.0	1	.3	
0.1	1.0	0.0	1	0.0	
1.0	1.0	0.0	1	0.0	
10.0	1.0	0.0	1	.15	

Table 20.—Step-Induced Failure Transients, Force Summed

Step (% of X_{max})	Disengaged channels (no.)	Output transient (1) (% of X_{max})
1	0	.05
10	0	0.6
1	1	0.1
10	1	0.7

(1) No failures detected

Table 21.—High Gain and Passive Failure Induced Transients, Force Summed

Failure category	System position offset (% of X_{max})	Disengaged channels (no.)	Output transients (% of X_{max})
High gain	0	0	2.3
High gain	25	0	–
High gain	0	1	2.3
Passive	0	0	1.0
Passive	25	0	1.0
Passive	0	1	1.2

Table 22.—Channel-Failure-Induced Performance Degradation, Force Summed

Disengaged channels	-3 dB Cutoff	Transition time	Hysteresis loss	Steady state output	
				5% command	90% command
(No.)	(Hz)	(Sec)	(% of X_{max})	(% of X_{max})	(% of X_{max})
0	15	.7	3	5	90
1	10	.75	4	4	85
2	9	.85	6	2.5	75

Table 23.—Safety/Maintenance Reliability Comparison

MTBF[(1)] (HRS)			
Active/standby		Force summed	
First failure	Total system loss	First failure	Total system loss
1110	4.115 (x 10^9)	910	1.339 (x 10^9)

(1) MTBF (Mean Time Between Failures) Based on 3-Hour Flight Duration For Total System Loss

4.0 SECONDARY ACTUATOR DESIGN CRITERIA

The previously discussed results of the analog computer and analytical studies in combination with the results of the piloted motion simulator study provide the basis to establish the actuator system's detailed definitions. This section summarizes the major criteria selection, limitations, and considerations, and establishes preliminary specifications for the actuator concepts.

4.1 DESIGN CRITERIA SELECTION

A summary of the allowable failure transients and actuator system failure transient characteristics is shown in table 24. The allowable transients are shown for a first failure condition and for a second failure condition. Both failure conditions are shown for a landing approach flight configuration and a high speed cruise flight configuration. This summary contains only one set of characteristics for the active/standby system, since there are no changes in performance following a failure switchover to a standby channel. For the force summed system, however, there are changes in performance as a channel failure occurs. Therefore, two sets of failure capability data are shown for the force summed system; one with four channels operating and one with three channels operating.

The allowable failure transients were established from the FSAA simulation testing. These tests are summarized in paragraph 2.3. The failure transient characteristics of the active/standby and force summed systems were determined from the analog computer study. The analog study results are summarized in paragraph 2.4.

No oscillatory failure monitoring system was incorporated in either of the two actuator system models evaluated. Therefore, as shown on the summary table (table 24), neither the active/standby nor the force summed system satisfies the oscillatory allowable failure transients.

The force summed actuator system satisfies the maximum allowable transients for all failure modes except the oscillatory failures.

The active/standby actuator system satisfies the maximum allowable transients for all failure modes except the step and oscillatory failures. In summary, the force summed system has the capability to satisfy the SST piloted requirements, with exception of the oscillatory transients. Whereas, the active/standby system tested has poorer failure transient performance as compared to the force summed system and does not totally satisfy the SST maximum allowable transients. The development of an improved failure monitor system would be required for the active/standby system to be competitive with the force summed system.

Additional failure transient capability is needed in both concepts to detect oscillatory failures.

4.2 DESIGN CRITERIA CONSIDERATIONS AND LIMITATIONS

Design criteria for the active/standby and force summed secondary actuator concepts were primarily based on the FSAA simulator test results. This simulator study evaluated the Boeing 2707-300 airplane, flown in a manual control mode. The test results are therefore typical for this airplane and its control systems.

Although criteria sensitivity to airplane model variations has not been established in this study, the criteria presented in this document are considered an appropriate base for other AST airplane configurations flown in a manual control mode.

When selecting design criteria for a secondary actuator application, consideration must be given to all requirements. In addition to the manual mode of operation, a typical transport type airplane will be equipped with an autopilot, an autoland system, and most likely in the case of an AST, some type of structural mode suppression system. Any, or all, of these systems can impose stringent requirements on the control system characteristics. The requirements of these automatic control functions are not defined in this document.

4.3 SECONDARY ACTUATOR DESIGN SPECIFICATION

Preliminary detailed actuator design definition for both the active/standby and force summed secondary actuator systems are included in tables 25 and 26. The criteria are based on the nominal baseline design parameters used in the study, modified consistent with the conclusions of this study.

Table 24.—Failure Transient Criteria/Capability Summary

Failure criteria	Maximum allowable transient (1)		Actuator system transient capability (% Xmax)		
				Force summed	
	1st failure	2nd failure	Active/ standby	1st failure	2nd failure
Step	12/5	38/18	10	.6	.7
High gain	12/5	38/18	3	2.3	2.3
Passive	12/5	38/18	3	1	1.2
Oscillatory (0.1 Hz)	0	0	7	.5	.5
Oscillatory (1 Hz)	8.5/1.5	27/-	8	.5	.5
Oscillatory (10 Hz)	–	–	2.5	.3	.3
Switch delay	1 sec	3.65 sec	–	–	–
Slowover	–	–	5	1.8	1.8

(1) Landing approach/high speed cruise

Table 25.—Active/Standby Actuator Design Specification

Unit criteria	S.I. Units	(U.S. Units)
Number of actuator channels	3	(3)
Piston area	$1.9 \times 10^{-4}\ m^2$	(.294 in^2)
Rated velocity	6.6×10^{-2} m/s	(2.6 in/s)
Force output/channel	4000	(900 lbf)
Open loop gain	60 sec^{-1}	(60 sec^{-1})
Maximum damping/channel	1400 N-s/m	(8 lbf-s/in)
Maximum friction/channel	1.8 N	(.4 lbf)
Resolution	2%	(2%)
Threshold	0.1%	(0.1%)
Linearity	±2%	(±2%)
Weight	10.4 Kg	(23 lb)
Total piston stroke	5.08×10^{-2} m	(2 in)
<u>Actuator Valve</u>		
Rated input voltage (max)	25 v	(25 v)
Flow gain	$6.6 \times 10^{-7}\ m^3$-mA/s	(.04 in^3-mA/s)
Pressure gain	6.9×10^{7} Pa/mA	(10^4 psi/mA)
<u>Monitor Valve</u>		
Rated input voltage (max)	25 v	(25 v)

Table 26.—Force Summed Actuator Design Specification

Unit Criteria	S.I. Units	(U.S. Units)
Number of actuator channels	4	(4)
Piston area	1.9×10^{-4} m^2	(.294 in^2)
Rated velocity	6.6×10^{-2} m/s	(2.6 in/s)
Force output/channel	1335	(300 lbf)
Open loop gain	60 sec^{-1}	(60 sec^{-1})
Maximum damping /channel	1400 N-s/m	(8 lbf-s/in)
Maximum friction/channel	1.8 N	(.4 lbf)
Resolution	2%	(2%)
Threshold	0.1%	(0.1%)
Linearity	±2%	(±2%)
Weight	13.6 Kg	(30 lb)
Total piston stroke	5.08×10^{-2} m	(2 in)
<u>Actuator Valve</u>		
Rated input voltage	25 v	(25 v)
Flow gain	6.6×10^{-7} m^3-mA/s	(.04 in^3-mA/s)
Pressure gain	1.52×10^{6} Pa/mA	(220 psi/mA)

5.0 ACTUATION CONCEPT APPLICABILITY

The previously discussed study results provide the basis to judge and to establish the applicability and practicality for using the two actuator concepts in an AST and other type aircraft control systems.

5.1 APPLICABILITY OF ACTUATOR CONCEPTS TO AST CONTROL SYSTEMS

AST airplanes will operate throughout a large speed and altitude range. Unstable configurations in the subsonic speed range will more than likely prevail. At higher supersonic speeds stability would increase. To operate these airplanes economically, stability margins must be selected such that flight-critical augmentation systems are required for safety of flight. Other characteristics of an AST affecting control system performance requirements are structural flexibility and control sensitivity at cruise.

The requirements on AST control system performance are great. Phase and gain characteristics must be rigorously controlled throughout the frequency spectrum within which these systems are to operate. Secondary servos will be used as intermediate signal conversion stages in augmentation systems as well as in other automatic control systems. Phase and gain variations in the secondary actuators must be held to a minimum by judiciously selecting linear actuator parameters and by minimizing nonlinear effects. Due to the high control effectivenss at cruise, failure transients due to channel failures must be minimized to avoid catastrophic upsets. As these augmentation systems are flight critical, system reliability must approach that of the airplane structure.

The comparison of the two secondary actuator concepts in section 2.0 indicates that the force summed concept meets performance requirements better than the active/standby concept. However, the active/standby is superior in meeting reliability requirements. Based on these observations the force summed secondary actuator system would be the most likely candidate for an AST application.

5.2 APPLICABILITY OF ACTUATOR CONCEPTS TO AIRCRAFT OTHER THAN AST

Conventional subsonic transport airplanes are normally stable vehicles that do not require stability augmentation other than to complement flying qualities characteristics. Secondary actuators are used in these types of aircraft in yaw damper and autopilot systems. Both of these system types operate in the low frequency ranges of rigid airplane dynamics. Frequency response requirements for these systems are relatively low. Control surface sensitivity on subsonic aircraft is normally low as compared to that of an AST, especially at cruise. With this low sensitivity, normal surface travel is relatively large. This, and the inherent stability of the airplane, require less stringent performance capabilities. Also, due to the reduced control surface sensitivity, upsets due to control system failure modes will be less severe than would the case for the AST.

For these reasons, more emphasis will be placed on characteristics such as maintainability and cost than on high performance when selecting a secondary actuator concept for this type of airplane. The comparison of the active/standby and force summed systems made in section 2.4, indicates that the active/standby system is superior in this respect. If, however, selections are to be made for subsonic advanced technology transports, the requirements on performance might well be as stringent as those for an AST.

A number of advanced technology augmentation systems are being considered. Examples are stability augmentation of airplane with relaxed static stability, load alleviation and mode suppression. All these control systems are augmenting marginally stable and unstable dynamics in an extended frequency spectrum. Therefore, the performance and reliability requirements may again become paramount. In the evaluation of the two concepts, the force summed system has the better performance and would be the most likely choice for an advanced technology airplane.